ROTARY FUEL INJECTION PUMP WEAR TESTING USING A 30%/70% ATJ/F-24 FUEL BLEND

INTERIM REPORT
TFLRF No. 488

By
Douglas M. Yost
Edwin A. Frame

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

For
Patsy A. Muzzell
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-15-C-0030 (WD12 Task 2.2)

October 2017

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A 30%/70% blend of ATJ/F-24 fuels at maximum CI/LI additive concentration were operated in rotary, mechanical, fuel-lubricated, fuel injection pumps for a 1000-hour target at 77 °C and 40 °C fuel inlet temperatures. Both tests with the 24-ppm CI/LI treatment lasted the 1000-hour duration, but with moderate wear and degraded fuel injection pump performance.

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F-24, ATJ, Alcohol to Jet, Alternative Fuels, General Engine Products 6.5LT, Rotary Fuel Injection Pump, Wear, Durability

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EXECUTIVE SUMMARY

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection system equipment durability. Two distinct tests were performed utilizing a 1000-hour fuel injection pump operating procedure:

1. A blend of 30/70 ATJ/F-24 with 24-ppm CI/LI with a fuel inlet temperature of 77 °C.
2. A blend of 30/70 ATJ/F-24 with 24-ppm CI/LI with a fuel inlet temperature of 40 °C.

Conclusions can be made from the cumulative knowledge of utilizing JP-8, F-24, synthetic aviation kerosene fuel blends, and 30/70 ATJ/F-24 in diesel rotary fuel injection pumps at various fuel inlet temperatures:

1. For elevated fuel inlet temperature operation, even with petroleum F-24 at 77 °C, the maximum effective CI/LI concentration is required to provide adequate wear protection.
2. For elevated fuel inlet temperature operation, with synthetic aviation fuel blends at 77 °C, the minimum effective CI/LI concentration is inadequate.
3. A 30/70 blend of ATJ/F-24 with 24-ppm CI/LI operated at both 40 °C and 77 °C fuel inlet temperatures will allow 1000-hours of rotary pump operation. However, the performance degradation of the fuel injection pumps at 1000-hours could impact engine operation, and component inspections suggest moderate wear.
4. The additional 5% ATJ in the test blend may have improved injection pump wear resistance due to a slight viscosity improvement.

The technical feasibility of using blends of ATJ/F-24 fuel at various temperatures and blend ratios in rotary fuel injection equipment when blended with a CI/LI additive has been investigated and it is recommended:

- At the minimum effective concentration of a QPL-25017 CI/LI additive, ATJ/F-24 blends should NOT be utilized in regions where rotary fuel injection pump equipped engines are continuously exposed to elevated fuel inlet temperatures.

- It is recommended that all blends of ATJ/F-24 fuels include the addition of the maximum effective concentration of CI/LI for use in diesel rotary fuel injection equipment at nominal ambient temperatures.
- At elevated fuel inlet temperatures, the use of maximum concentration CI/LI in a 25% ATJ/F-24 fuel blend appears to result in accelerated wear in fuel-lubricated rotary fuel injection pumps.
- At various fuel inlet temperatures, the use of maximum concentration CI/LI in a 30% ATJ/F-24 fuel blend appears to retard the accelerated wear observed in prior fuel-lubricated rotary fuel injection pump studies.
- ATJ can be utilized at 30% when blended with F-24, provided the F-24 component has sufficient cetane number such that the resulting blend is 40 CN or greater.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period September 2013 through September 2017 under Contract No. W56HZV-15-C-0030. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative and the project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical and administrative support staff.

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ACRONYMS AND ABBREVIATIONS

° C .... degrees Centigrade
ASTM .... ASTM International
ATJ .... Alcohol to Jet Fuel
BOCLE .... Ball-on-Cylinder Lubricity Evaluator
cc .... Cubic Centimeter
CI/LI .... Corrosion Inhibitor/Lubricity Improver
cm .... Centimeter
cSt .... Centistokes
F-24 .... Jet A fuel with additives, NATO code
ft .... Foot
FT-SPK .... Fischer-Tropsch Synthetic Paraffinic Kerosene
HEFA .... Hydro-treated Esters and Fatty Acid(s)
HFRR .... High Frequency Reciprocating Rig
HMMWV .... High Mobility Multi-Purpose Wheeled Vehicle
hr .... Hour
in .... Inch
JP-8 .... Jet Propulsion 8
kW .... Kilowatt
L .... Liter
lb .... Pound
m .... Meter
mg .... milligram
mg/L .... milligrams per Liter concentration
mL .... milliliter
mL/min .... milliliter/minute
mm .... millimeter
ppm .... parts per million
psig .... pounds per square inch, gauge
QPL .... Qualified Products List
RPM .... rotation(s) per minute
SwRI® .... Southwest Research Institute®
SOW .... Scope of Work
SPK .... Synthetic Paraffinic Kerosene
TACOM .... Tank Automotive and Armaments Command
TARDEC .... Tank Automotive RD&E Center
TFLRF .... TARDEC Fuel and Lubricants Research Facility
WOT .... Wide Open Throttle
WD .... Work Directive
WSD .... Wear Scar Diameter

1.0 BACKGROUND & INTRODUCTION

The United States Department of Defense Operational Energy Strategy has outlined a goal "to diversify its energy sources and protect access to energy supplies to have a more assured supply of energy for military missions"[1]. In accordance with this directive, the U.S. Army had conducted extensive research to investigate alternative fuels viability in military equipment. This has included basic chemical and physical property investigation to identify surrogate fuel sources with similar properties as traditional petroleum fuels, to full scale equipment and fleet testing to determine resulting component and vehicle performance. This report covers investigation into the use of blended Alcohol to Jet (ATJ) based fuel and traditional petroleum derived F-24 in a fuel sensitive rotary fuel injection pump at various fuel inlet temperatures. All work was completed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI) in San Antonio, TX.

Initial tests with synthetic aviation kerosene fuels revealed severe wear and extreme life reduction of rotary fuel injection pumps for diesel engines. The untreated fuels caused performance degrading wear on rotary fuel injection pumps within 25-hours of operation on the untreated fuel. However, prior work with synthetic fuels have shown those fuels responded well to the addition of a Corrosion Inhibitor/Lubricity Improver (CI/LI) additive to extend the life of the rotary fuel injection equipment. In addition, it is likely that most synthetic fuel will be used as a blending component with petroleum F-24 fuel at a maximum 50-percent in order to maintain fuel density above the F-24 specification minimum.

In conducting previous additive treated synthetic fuel pump stand tests, it was found that the tests could be operated to conclusion at 500-hours if the maximum concentration of CI/LI additive is utilized at 40 °C fuel inlet temperature. Prior testing also indicated a synthetic fuel that is blended 50-percent with F-24, and treated with an approved CI/LI additive, will also provide adequate diesel fuel injection pump wear protection at 40 °C fuel inlet temperature.

2.0 TEST OBJECTIVE

The objective of this test was to evaluate the durability of the fuel injection system utilized on a V8-cylinder General Engine Products (GEP) 6.5L engine with a 30%ATJ/70%F-24 fuel blend at various fuel inlet temperatures for 1000-hours.

3.0 TEST APPROACH

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection equipment durability. The test series attempted to determine the level of fuel injection system degradation due to wear and failure of the boundary film using the HMMWV engine opposed-piston, rotary distributor, fuel injection pumps with an Alcohol-to-Jet (ATJ) synthetic fuel blended with petroleum F-24 with CI/LI additive treatments. Two distinct tests were performed utilizing a fuel injection pump operating procedure with targeted 1000-hours of operation. The specific tests performed included:

1. Blend of 30-percent ATJ and 70-percent F-24, the maximum level of DCI-4A CI/LI additive specified as 24-ppm, with a fuel inlet temperature of 77 °C.
2. Blend of 30-percent ATJ and 70-percent F-24, the maximum level of DCI-4A CI/LI additive specified as 24-ppm, with a fuel inlet temperature of 40 °C.

3.1 FUEL PROPERTIES

The fuel blend was additized consistent to AFLP-3747 NATO F-24 fuel specifications. All additive concentrations blended sufficient for the total blended volume (target concentrations: 24g/m^3 CI/LI, 1g/m^3 STADIS, 0.09% FSII). Blending of the ATJ and F-24 occurred in bulk on-site at TFLRF. Table 1 presents the chemical and physical properties of the neat F-24 (AF-9623) and the tested 30% ATJ blend (AF-9625). Table 2 shows the speed of sound and bulk modulus data for the 30/70 ATJ/F-24 and F-24 test fuels.

Table 1. 30% ATJ Blend & Neat F-24 Chemical & Physical Properties

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Saybolt Color	**D156**	--	26	22
Acid Number	**D3242**	mg KOH / g	0.006	0.006
Chemical Composition	**D1319**			
Aromatics		vol %	12.9	18.7
Olefins		vol %	0.6	0.6
Saturates		vol %	86.5	80.7
Sulfur Content - XRF	**D2622**	ppm	850.22	1202.49
Sulfur Mercaptan	**D3227**	mass%	0.0	0.0
Doctor Test	**D4952**	--	Sweet	Sweet
Distillation	**D86**			
IBP		°C	170.3	168.8
5% Rcvd		°C	178.6	178.3
10% Rcvd		°C	179.2	181.3
15% Rcvd		°C	181.8	184.2
20% Rcvd		°C	183.8	187.3
30% Rcvd		°C	187.6	192.7
40% Rcvd		°C	191.6	198.2
50% Rcvd		°C	196.3	203.7
60% Rcvd		°C	202.0	209.6
70% Rcvd		°C	210.6	217.1
80% Rcvd		°C	222.7	227.0
90% Rcvd		°C	237.9	240.1
95% Rcvd		°C	249.2	251.2
FBP		°C	262.5	262.8
Residue		%	0.8	0.8
Loss		%	0.8	1.3
T50-T10		°C	17.1	22.4
T90-T10		°C	58.7	58.8
Flash Point by Tag Closed Cup Tester	**D56**	°C	51	52
Density 15°C	**D4052**	kg/m^3	784.4	795.2
Freeze Point (Manual)	**D2386**	°C	-56.0	-55.0
Net Heat of Combustion	**D4809**	BTU/lb	18692.0	18546.0
Hydrogen Content (NMR)	**D3701**	mass %	14.36	13.99
Smoke Point	**D1322**	mm	26.8	24.7
Naphthalene Content	**D1840**	vol%	1.20	0.89
Gum Content	**D381**	mg/100 mL	2	1

Table 1(Cont'd). 30% ATJ Blend & Neat F-24 Chemical & Physical Properties

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Copper Strip Corrosion	**D130**			
Test Temperature		°C	1A	1A
Test Duration		hrs	100	100
Rating		--	2.0	2.0
JFTOT	**D3241**			
Test Temperature		°C	260	260
ASTM Code		rating	1	1
Maximum Pressure Drop		mmHg	0	0
Ellipsometer		nm	5.207	4.144
Total Volume		cm^3	1.0000E-06	1.0000E-06
Test Temperature		°C	325.0	325.0
ASTM Code		rating	4P	2.0
Maximum Pressure Drop		mmHg	0.0	0.0
Ellipsometer		nm	247.575	61.854
Total Volume		cm^3	--	7.00E-06
Particulate Contamination in Aviation Fuels	**D5452**			
Total Contamination		mg/L	4.40	4.60
Total Volume Used		mL	1000	1000
Water Reaction	**D1094**			
Volume Change of Aqueous Layer		mL	1.0	1.0
Interface Condition		rating	1B	1B
Separation		--	2	2
MSEP	**D3948**	rating	62	67
Fuel System Icing Inhibitor (FSII) Content	**D5006**			
Test Temperature		°C	20.5	20.5
FSII Content		vol %	0.14	0.14
Electrical Conductivity	**D2624**			
Electrical Conductivity		pS/m	0	453
Temperature		°C	20.8	19.9
Calculated Cetane Index	**D976**	--	49.3	48.0
Cetane Number	**D613**	--	40.8	49.4
Derived Cetane Number (IQT)	**D6890**			
Ignition Delay		ms	5.013	4.324
Derived Cetane Number		--	41.68	47.62

Table 1(Cont'd). 30% ATJ Blend & Neat F-24 Chemical & Physical Properties

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Kinematic Viscosity	**D445**			
Test Temperature		°C	100	100
Viscosity		mm²/s	0.69	0.67
Test Temperature		°C	40	40
Viscosity		mm²/s	1.32	1.28
Test Temperature		°C	-20	-20
Viscosity		mm²/s	4.352	4.215
Lubricity (BOCLE)	**D5001**	mm	0.560	0.563
Lubricity (HFRR)	**D6079**			
Test Temperature		°C	60	60
Wear Scar Diameter		µm	759	760
Hydrocarbon Types by Mass Spec.	**D2425**			
Paraffins		mass %	60.8	52.8
Monocycloparaffins		mass %	23.9	25.7
Dicycloparaffins		mass %	0.0	0.0
Tricycloparaffins		mass %	0.0	0.0
Total Napthenes		mass%	23.9	25.7
TOTAL SATURATES		mass %	84.7	78.5
Alkylbenzenes		mass %	10.3	14.3
Indans/Tetralins		mass %	3.4	4.8
Indenes		mass %	0.2	0.4
Naphthalenes		mass %	0.3	0.4
Alkyl Naphthalenes		mass %	0.9	1.3
Acenaphthenes		mass %	0.1	0.1
Acenaphthylenes		mass %	0.1	0.1
Tricyclic- Aromatics		mass %	0.0	0.0
Total Polynuclear Aromatics (PNAs)		mass %	1.4	1.9
TOTAL AROMATICS		mass %	15.3	21.4
Karl Fischer Water Content	**D6304**	ppm	54	59
Elemental Analysis	**D7111**			
Al		ppb	<100	<100
Ba		ppb	<100	<100
Ca		ppb	585	379
Cr		ppb	<100	<100
Co		ppb	578	353
Cu		ppb	<100	<100
Fe		ppb	<100	<100

Table 1(Cont'd). 30% ATJ Blend & Neat F-24 Chemical & Physical Properties

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Pb		ppb	<100	<100
Elemental Analysis (Cont'd)	**D7111**			
Li		ppb	<100	<100
Mg		ppb	154	<100
Mn		ppb	<100	<100
Mo		ppb	<100	<100
Ni		ppb	<100	<100
Pd		ppb	<100	<100
P		ppb	<1,000	<1,000
Pt		ppb	<100	<100
K		ppb	<1,000	<1,000
Si		ppb	<100	<100
Ag		ppb	<100	<100
Na		ppb	<1,000	<1,000
Sr		ppb	<100	<100
Sn		ppb	<100	<100
Ti		ppb	<100	<100
V		ppb	<100	<100
Zn		ppb	<100	<100
Nitrogen Content	**D4629**	mg/kg	<1.0	<1.0
Carbon Hydrogen	**D5291**			
Carbon		mass%	84.56	85.16
Hydrogen		mass%	14.28	13.98
Micro Separation (MSEP)	**D7224**	--	86	81

Table 2. Bulk Modulus of 30% ATJ Blend and Neat F-24 Fuels

Bulk Modulus CL16-0368, AF-9625, 30% ATJ Blend				
Temperature (°C)	**Pressure (psi)**	**Density (g/mL)**	**SOS (m/s)**	**Bulk Modulus (psi)**
29.8	0	0.7735	1251.7	175,762
30.6	1101	0.7798	1297.0	190,249
30.6	2060	0.7844	1326.6	200,202
30.6	3023	0.7887	1369.1	214,430
30.6	3843	0.7923	1397.9	224,554
30.6	5463	0.7988	1459.3	246,734
64.6	0	0.7477	1117.7	135,485
67.8	1129	0.7560	1173.0	150,847
67.8	2218	0.7627	1218.1	164,123
67.8	3233	0.7680	1260.1	176,873
67.8	4025	0.7718	1289.9	186,258
64.8	4988	0.7764	1318.7	195,833
80.0	0	0.7363	1064.2	120,949
80.2	1390	0.7472	1126.0	137,395
80.2	1994	0.7512	1157.4	145,957
80.2	3085	0.7576	1203.4	159,138
80.2	4029	0.7625	1248.1	172,265
80.2	5131	0.7679	1285.1	183,946
Bulk Modulus CL16-0369, AF-9623, Neat F-24				
Temperature (°C)	**Pressure (psi)**	**Density (g/mL)**	**SOS (m/s)**	**Bulk Modulus (psi)**
29.6	0	0.7843	1270.7	183,661
31.0	1208	0.7893	1322.5	199,937
31.0	2066	0.7937	1353.3	210,519
31.0	2890	0.7973	1381.8	220,483
31.0	3693	0.8004	1413.4	231,594
31.0	5298	0.8073	1473.2	253,769
65.4	0	0.7576	1137.9	142,270
64.8	1229	0.7661	1194.9	158,649
64.8	2026	0.7704	1224.2	167,472
64.8	3119	0.7763	1271.8	182,122
64.8	3965	0.7804	1298.4	190,817
64.8	5123	0.7856	1352.6	208,457
79.8	0	0.7469	1088.4	128,336
79.2	1219	0.7556	1147.8	144,368
79.2	2250	0.7617	1191.6	156,870
79.2	3117	0.7668	1220.3	165,613
79.2	4189	0.7723	1262.2	178,454
79.2	5238	0.7774	1311.8	194,014

3.2 STANADYNE ROTARY FUEL INJECTION SYSTEM

Rotary distributor fuel injection pumps are fuel lubricated, thus sensitive to fuel lubricity. Highly refined, low sulfur and low aromatic fuels can cause substantial performance degradation with these pumps. Wear seen in the Stanadyne pumps could be interpolated to rotary distributor pumps of other manufacturers.

3.3 PUMP TEST PROCEDURE

Full-scale equipment tests were performed using new fuel injection pumps and fuel injectors with each test fuel. The pump tests were performed in duplicate in order to obtain average wear results. Four fifty-five gallon drums of the appropriate test fuel are normally required for each 1000-hour pump tests. The 1000-hour tests were performed under steady state conditions at maximum fuel delivery for the test pump, as summarized in Table 3. The tests were occasionally halted and restarted as necessary due to scheduling requirements or technical reasons. The pumps were started gradually to prevent seizure due to thermal shock. To further reduce the risk of seizure due to differential expansion, the fuel was not preheated prior to starting the pumps.

Table 3. Pump Operating Conditions

Parameter:	Value:
Duration, hrs	1000
Speed, RPM	1700
Fuel Inlet Temperature, °C	77 or 40
Throttle position	Full
Fuel-drum temperature, °C	<30

The test stand included injection flow and pump return pipes, lift pumps, filters, flow meters, a fuel pre-heater and a heat exchanger to reduce the temperature of the fuel before returning to the storage tank. A schematic diagram of the fuel supply system proposed for the pump stand is shown in Figure 1. The temperature of the incoming fuel to each fuel injection pump was controlled to either 77 °C or 40 °C. The high-pressure outlets from the pumps were connected to fuel injectors assembled in a collection canister.

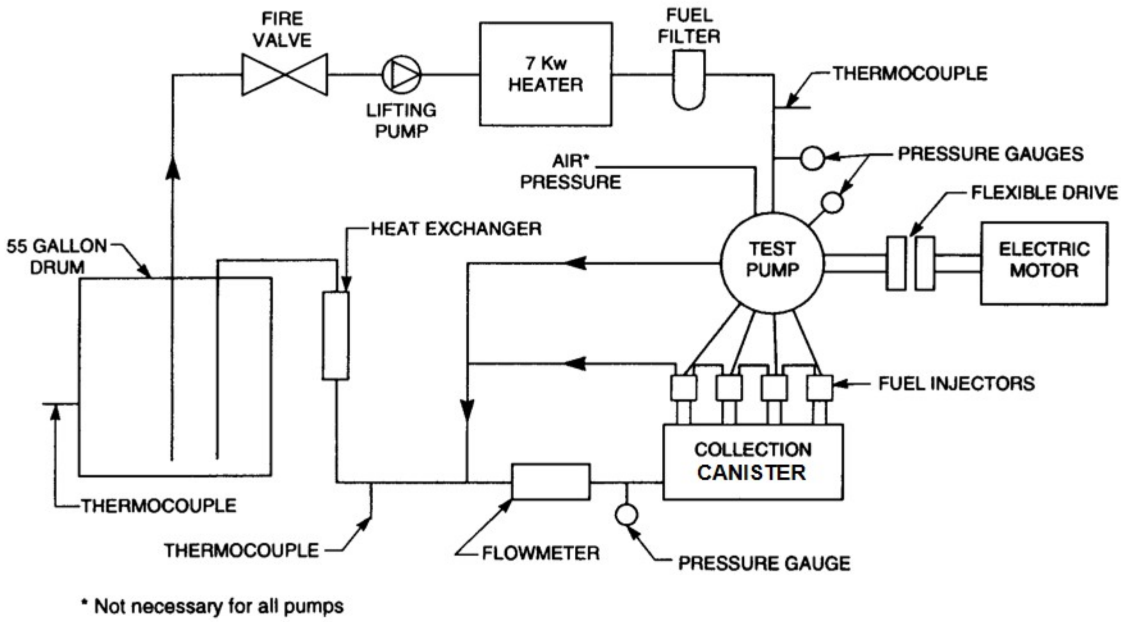


Figure 1. Schematic Diagram of Fuel Delivery System

3.4 LABORATORY SCALE WEAR TESTS

Stanadyne has indicated the lubricity of the test fuel should be determined prior to testing. Stanadyne has recommended the test fuel be changed at 250-hour intervals. The laboratory scale wear performed on the test fuels was the Ball on Cylinder Lubricity Evaluator procedure described in ASTM D-5001, because that procedure is called out for aviation kerosene fuels and additives. The ASTM D-6079 High Frequency Reciprocating Rig (HFRR) wear tests were also performed on the test fuels. The bench test results are shown in Table 4, with the 500-hour and 1000-hour samples being from the drums that completed 250-hours of test time. The overall results were quite consistent, suggesting recirculating the fuel does not substantially alter the test fuel severity.

Table 4. Beach Wear Test Results for 30/70 ATJ/F-24 with 24g/m^3 CI/LI Concentration

Test	ASTM Method	Units	Sample ID CL17-0525 Results	Sample ID CL17-0610 Results	Sample ID CL17-0707 Results	Sample ID CL17-0966 Results	Sample ID CL17-1043 Results	Sample ID CL17-1311 Results
			0-hour 77 ºC	500-hour 77 ºC	1000-hour 77 ºC	0-hour 40 ºC	500-hour 40 ºC	1000-hour 40 ºC
Lubricity (BOCLE)	**D5001**	mm	0.540	0.575	0.569	0.555	0.552	0.555
Lubricity (HFRR)	**D6079**	µm	723	715	722	718	733	737

3.5 EVALUATION OF THE PUMPS USING A CALIBRATED TEST STAND

Prior to and following each scheduled pump test, the performance of each of the Stanadyne pumps was evaluated using a calibrated test stand. The objective of the calibration stand evaluation is to define the effect of the durability testing on pump performance. The calibration stand evaluations were performed at an authorized pump distributor. No adjustments were made to any of the pumps to achieve the manufacturer's specifications, either before, during, or following the scheduled pump stand tests.

The appropriate inspection and test procedures for determining fuel injector performance were followed prior to, and after each fuel evaluation.

3.6 PUMP DISASSEMBLY AND WEAR EVALUATION

The fuel injection pumps and fuel injectors were disassembled at SwRI® following completion of the durability tests and the subsequent evaluation using the calibrated test stand. A SwRI disassembly and rating procedure was originally developed for the U.S. Army for use with Stanadyne fuel injection equipment. Each sliding contact within the pump is rated on a scale from 0 to 5, with 0 corresponding to no wear and 5 corresponding to severe wear and failure. The wear scars on components throughout the pump are evaluated visually and quantitative measurements of wear volume were made on the critical pump components. The SwRI procedure looks at all wear contacts within the fuel injection pump, which are lubricated by the fuel.

4.0 PUMP TEST STAND EVALUATIONS

4.1 ROTARY PUMP TEST PROCEDURE

The Stanadyne arctic pumps used for this program are opposed-piston, inlet-metered, positive-displacement, rotary-distributor, fuel-lubricated injection pumps, model DB2831-6282, for a General Engine Products 6.5L turbocharged engine application. The arctic pump is equipped with hardened transfer pump blades, transfer pump liner, governor thrust washer, and drive shaft tang to reduce wear in these critical areas of the pump. A schematic diagram of the principal pump components is provided in Figure 2.

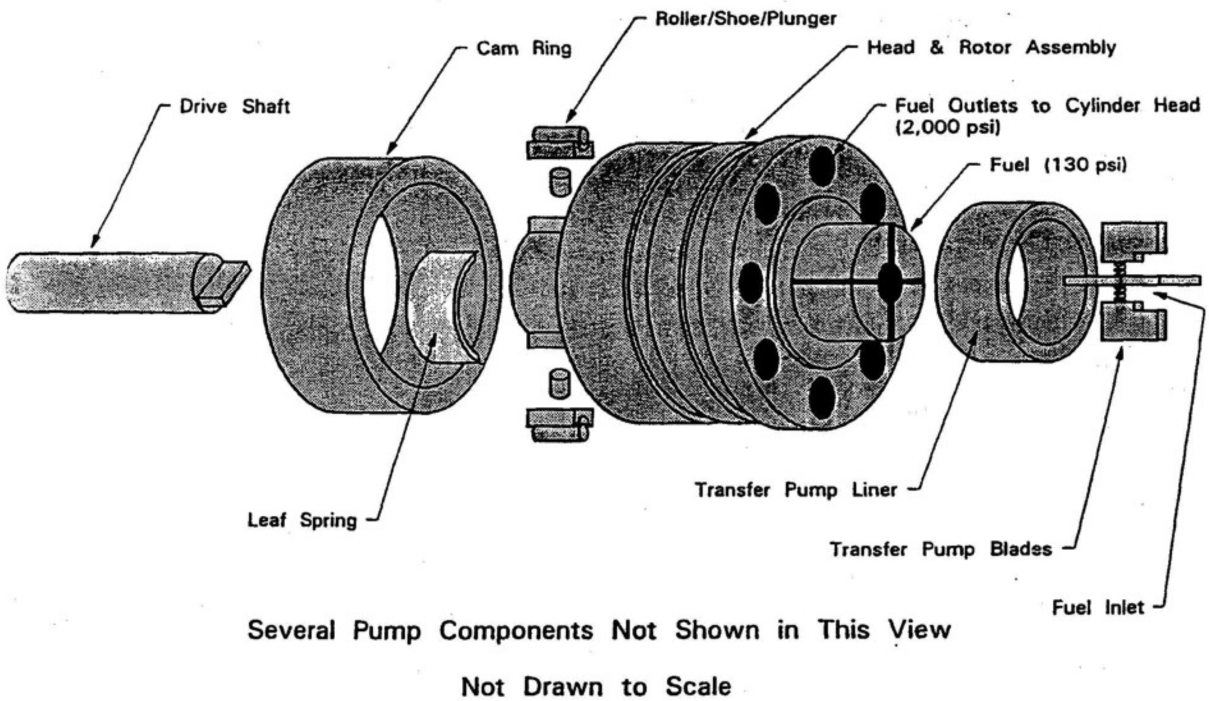


Figure 2. Schematic Diagram of Principal Pump Components

The new pumps were disassembled, and pre-test roller-to-roller dimensions and transfer pump blade heights were obtained. Roller-to-roller dimensions were set per Stanadyne Diesel Systems Injection Pump Specifications for the DB2831-6282 model. The specification calls for a roller-to-roller dimension setting of 50.19 mm ± .026 mm, with a 0.2 mm maximum eccentricity. All pumps were set prior to testing with instructions that the roller-to-roller dimension not be adjusted during pre- and post-performance evaluations so that wear in these components could be accurately measured. Although there are not any min-max specifications other than initial assembly values, wear calculation from the roller-to-roller dimension is an excellent benchmark for the effects of fuel lubricity.

The pumps were reassembled and pre-test performance evaluations were conducted. The pumps were then mounted on the test stand and operated at 1700-RPM; with the fuel levels in the wide open throttle position (WOT) for targeted 1000-hour increments (or less). Fuel flow, fuel inlet and outlet temperatures, transfer pump, pump housing pressures, and RPM were tracked and recorded. Flow meter readings reflect the injected fuel from the eight fuel injectors in each collection canister. Any

wear in the fuel injection pump metering section was reflected as an increased or reduced flow reading. For these sets of tests the fuel inlet temperature control targets were either 77 °C or 40 °C. Fuel inlet temperature variations directly can affect the fuel return temperature; the fuel return temperature is a function of accelerated pump wear. The transfer pump pressure is the regulated pressure the metal blade transfer pump supplies to the pump metering section. With low lubricity fuels, wear is likely to occur in the transfer pump blades, blade slot, and eccentric liner. Wear in these areas generally causes the transfer pump pressure to decrease. However, because the transfer pump has a pressure regulator, significant wear needs to occur in the transfer pump before the fuel pressure drops to below the operating range allowed in the pump specification. The housing pressure is the regulated pressure in the pump body that affects fuel metering and timing. With low lubricity fuel, wear occurs in high fuel pressure generating opposed plungers and bores, and between the hydraulic head and rotor. Leakage from the increased diametrical clearances of the plunger bores and the hydraulic head and rotor, results in increased housing pressures. Increased housing pressure reduces metered fuel and retards injection timing.

4.2 PUMP TEST STAND

The rotary pumps were tested on a drive stand with a common fuel supply. To insure a realistic test environment, the mounting arrangement and drive gear duplicate that of the 6.5LT engine. The fuel was maintained in a 55-gallon drum and continuously recirculated throughout the duration of each test. A gear pump provided a positive head of 3 psig at the inlet to the test pumps. A cartridge filter rated at 2 microns was used to remove wear debris and particulate contamination. Finally, a 7-kW Chromalox explosion-resistant circulation heater produced the required fuel inlet temperature.

The high-pressure outlets from the pumps were connected to eight Bosch Model O432217276 fuel injectors for a 6.5LT engine and assembled in a collection canister. Fuel from both canisters was then returned to the 55-gallon drum. A separate line was used to return excess fuel from the governor housing to the fuel supply. Fuel-to-water heat exchangers on both the return lines from the injector canisters and the governor housing were used to cool the fuel. The test stand with pumps mounted is shown in Figure 3.

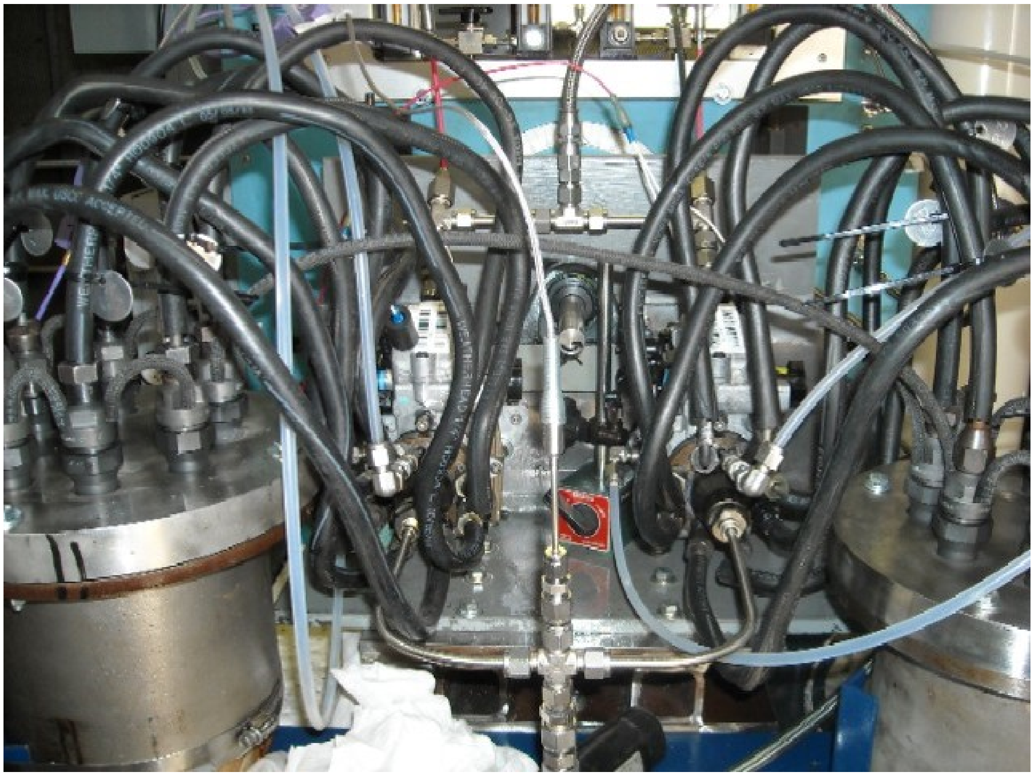


Figure 3. Dual Stanadyne Rotary Fuel Injection Pumps Mounted on Stand with Fuel Injectors

A data acquisition and control system recorded pump stand RPM, fuel inlet pressure, fuel inlet and return temperature, transfer pump pressures, pump housing pressures, and fuel flow readings. The entire rig was equipped with safety shutdowns that would turn off the drive motor in the event of low fluid level in the supply drum, high inlet and return fuel temperature (100 ºC), or low or high transfer pump and housing pressure. Since high-return fuel temperature is a precursor of accelerated wear, this fail-safe feature reduces the possibility of head and rotor seizure.

5.0 ROTARY FUEL INJECTION PUMP EVALUATIONS AND RESULTS

5.1 30/70 ATJ/F-24 WITH 24-PPM CI/LI FUEL AT 77 °C

The Stanadyne model DB2831-6282 rotary fuel injection pumps were received from a supplier and the pumps appeared to be in good condition. The fuel injection pumps were installed on the test stand and the pumps were operated for an hour to validate their operation and to run-in the components with a good lubricity calibration fluid. The pumps were run for 30-minutes at 1200-RPM pump

speed, with a half-rack fuel flow setting. For the final 30-minutes of the run-in the pumps were operated at the test condition of 1700-RPM pump speed, with a full-rack fuel flow setting.

The test bench and pumps were flushed with isooctane to attempt to remove any remaining run-in fluid. The isooctane was forced through the fuel injection pumps with pressure; the pumps were not run with isooctane in them. Following the isooctane flush, the treated F-24 was introduced into the test stand and the stand was operated at an idle condition until 2L of fuel was flushed through each set of eight injectors.

The first pump test was initiated with the maximum level CI/LI additive blend at a 77 °C fuel inlet temperature. The testing with the blend was initiated and the fuel injection pumps and stand control system appeared to function properly. The operating summaries for the respective fuel injection pumps are shown in Table 5, averaged over the operating interval for each pump, 1000-hours for pump SN:17200043 and 1000-hours for pump SN:17200045.

Table 5. 30/70 ATJ/F-24 with 24-ppm CI/LI Pump Operating Summary

Parameter	Unit	Averages	Std. Dev.
Pump Speed	RPM	1700	1
Fuel Inlet Pressure	psig	3.05	0.23
Fuel Inlet Temperature	^{0}C	76.9	0.4
Housing Pressure, SN:17200043	psig	13.42	1.05
Housing Pressure, SN:17200045	psig	13.24	1.07
Transfer Pump Pressure, SN:17200043	psig	70.97	0.42
Transfer Pump Pressure, SN:17200045	psig	83.58	2.43
Pump Fuel Return Temperature, SN:17200043	^{0}C	82.8	0.9
Pump Fuel Return Temperature, SN:17200045	^{0}C	84.1	0.8
Injected Flow Rate, SN:17200043	mL/min	779.3	6.9
Injected Flow Rate, SN:17200045	mL/min	795.3	22.0

The fuel injection pump delivery histories are shown in Figure 4 for both fuel injection pumps for operation on the ATJ/F-24 fuel with 24-ppm CI/LI at 77 °C fuel inlet temperature. Injection pump SN:17200043 revealed very slight variable delivery characteristics, with a gradual increase in delivery towards the end of testing. Injection pump SN:17200045 displayed somewhat erratic delivery, with a sudden increase in delivery around 425-hours, followed by a steady decay. In these pumps erratic delivery could be due to metering valve wear, governor linkage wear, or excessive

backlash due to drive tang wear. The pump drive speed was very consistent throughout the test, indicating very little governor wear and delivery interaction. The sole deviation of the pump speed and delivery in Figure 4 was due to a power failure.

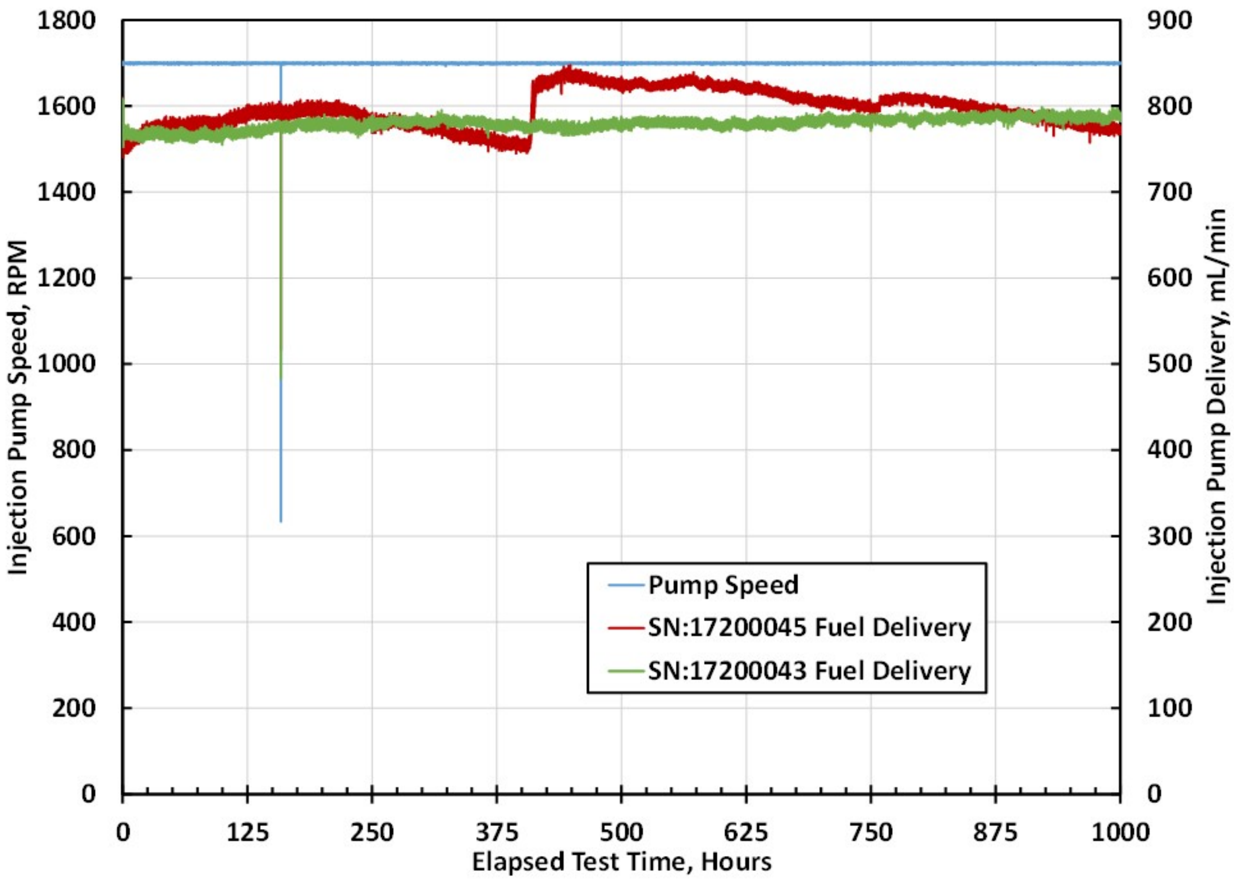


Figure 4. Injection Pump Delivery Histories for 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC Elevated Temperature

The fuel injection pump temperature histories are shown in Figure 5 for both fuel injection pumps for operation on ATJ/F-24 fuel with 24-ppm CI/LI at 77 °C fuel inlet temperature. Prior to test completion with either fuel injection pump, the housing fuel return temperatures are seen to increase at various times, due to increased internal friction in the fuel injection pumps. Pump SN:17200045 had higher return temperatures, possibly related to the more erratic delivery characteristics

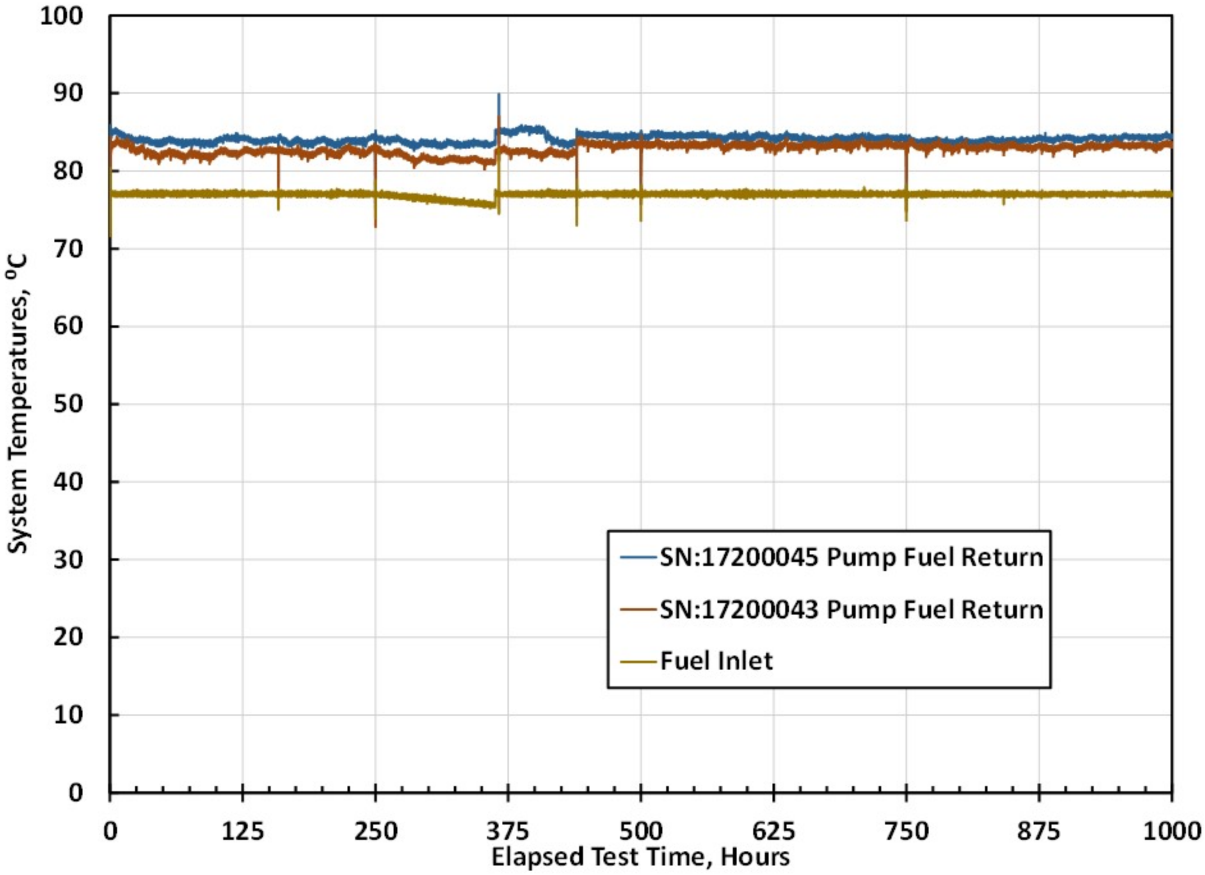


Figure 5. Fuel Inlet and Fuel Housing Return Temperatures for 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 °C Elevated Temperature

Shown in Figure 6 are the pressure histories for the elevated temperature ATJ/F-24 fuel with 24-ppm CI/LI testing. Both fuel injection pumps revealed slight variations in fuel delivery resulting in a slight increase in housing pressure towards the end of testing. Housing pressure usually increases in these pumps when an excessive amount of high-pressure fuel leaks past the pumping plungers, indicating an increase of the plunger-to-bore clearance. The transfer pump pressure histories for both pumps indicate wear in the transfer pump and transfer pump regulator led to some erratic transfer pump pressure histories. Fluctuations in the transfer pump pressure mirrors the fluctuations in pump fuel delivery. For both pumps the transfer pump pressures became more erratic towards the end of testing.

At 1000-hours of testing the tops of both fuel injection pumps were removed for inspection and an indication of wear debris. The housing for pump SN:17200043 is shown in Figure 7 and there is very little wear debris, with light amber housing staining evident. The housing for pump SN:17200045 is shown in Figure 8, for which minimal wear debris is evident along with very light amber staining of the housing.

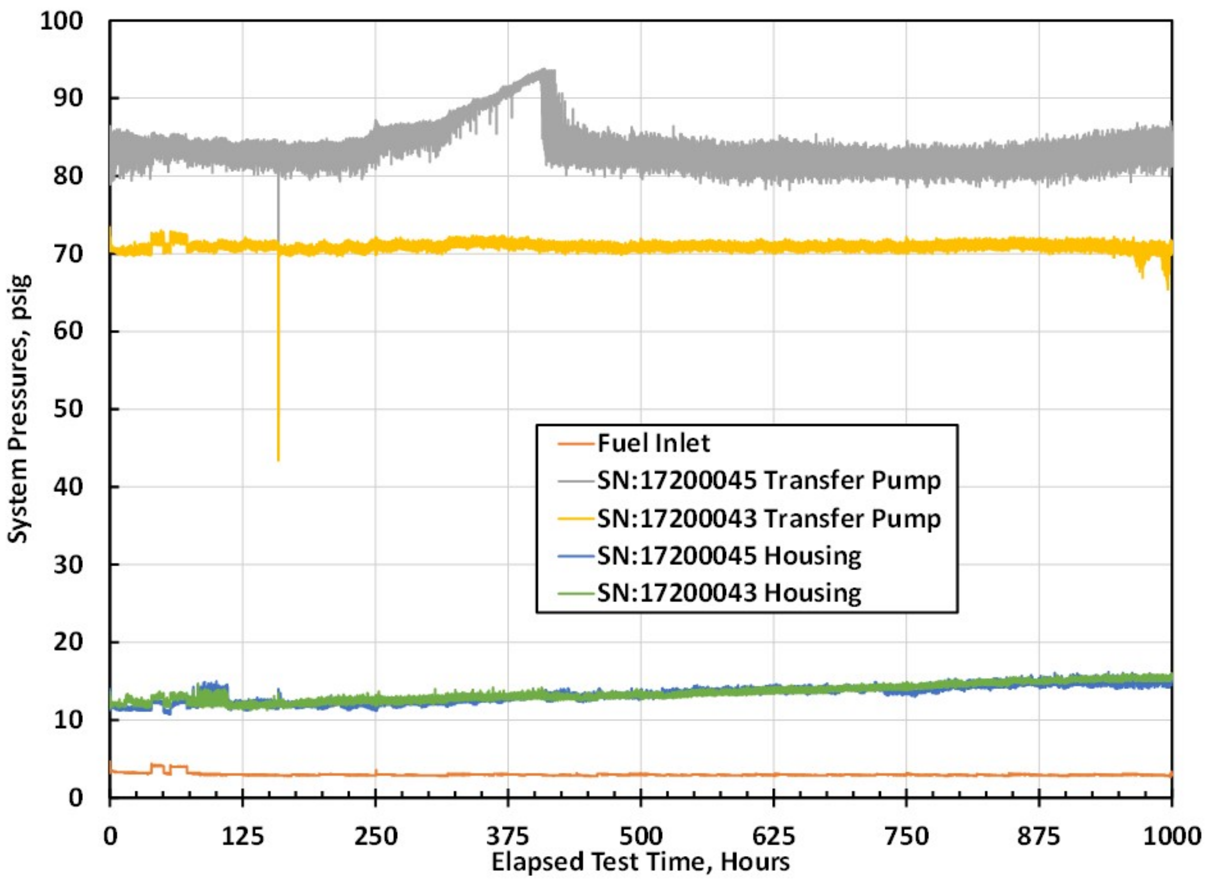


Figure 6. Fuel Inlet, Fuel Transfer Pump, and Housing Pressure Histories for 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC Elevated Temperature

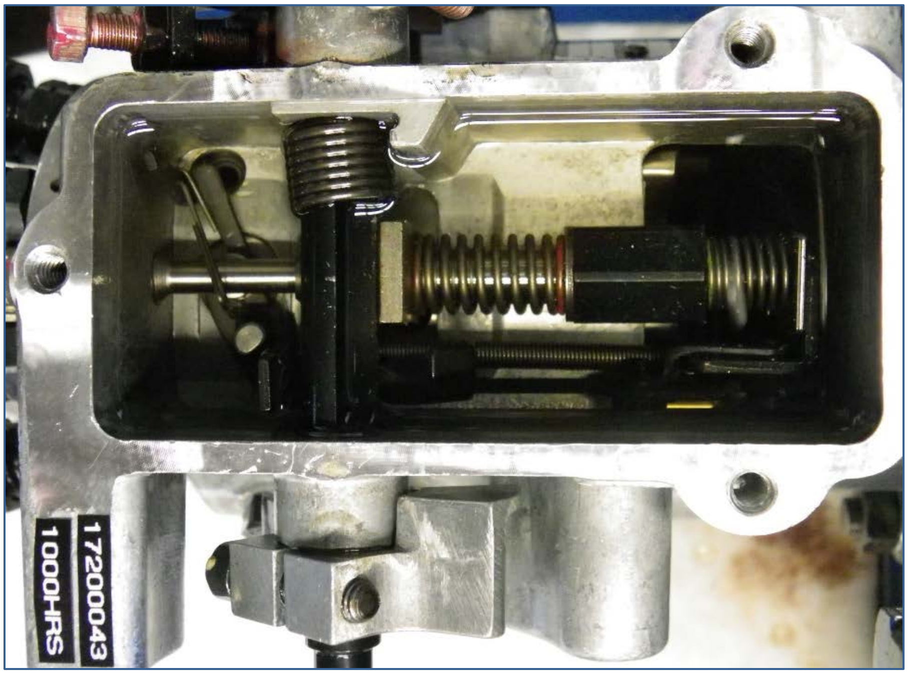


Figure 7. Pump SN:17200043 Showing the Wear Debris at 1000-Hours with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77°C Inlet Temperature

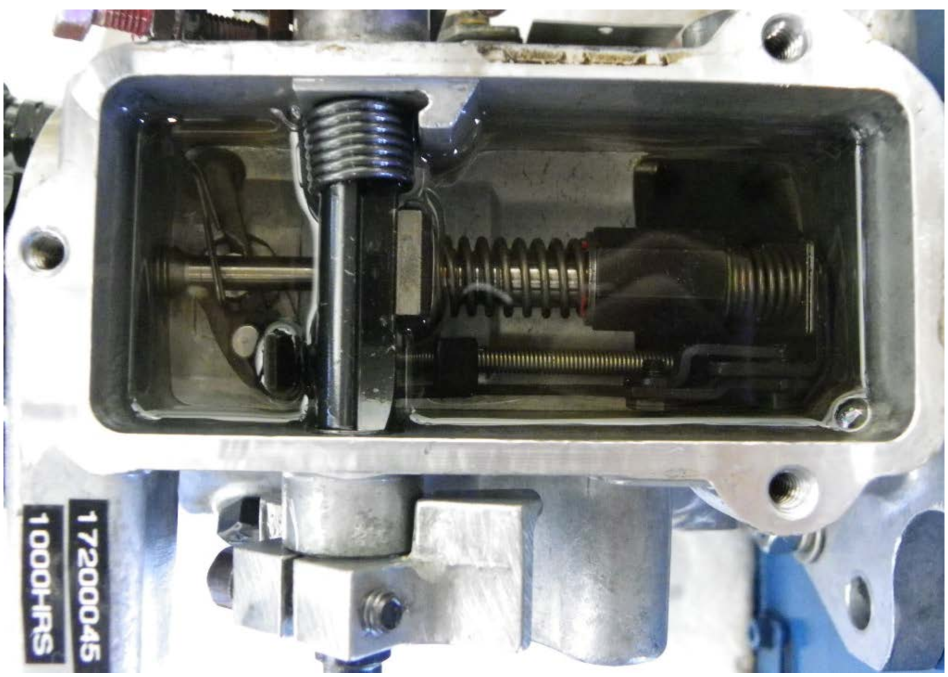


Figure 8. Pump SN:17200045 Showing the Wear Debris at 1000-Hours with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77°C Inlet Temperature

5.2 30/70 ATJ/F-24 WITH 24-PPM CI/LI FUEL AT 40 °C

Two Stanadyne model DB2831-6282 fuel injection pumps were installed on the test stand and the pumps were operated for an hour to validate their operation and to run-in the components with a good lubricity calibration fluid. The pumps were run for 30-minutes at 1200-RPM pump speed, with a half-rack fuel flow setting. For the final 30-minutes of the run-in the pumps were operated at the test condition of 1700-RPM pump speed, with a full-rack fuel flow setting.

The test bench and pumps were flushed with isooctane to attempt to remove any remaining run-in fluid. The isooctane was forced through the fuel injection pumps with pressure; the pumps were not run with isooctane in them. Following the isooctane flush, the treated ATJ/F-24 fuel was introduced into the test stand and the stand was operated at an idle condition until 2L of fuel was flushed through each set of eight injectors.

The testing with the ATJ/F-24 fuel with 24-ppm CI/LI was initiated and the fuel injection pumps and stand control system functioned normally. The operating summaries for the respective fuel injection pumps are shown in Table 6, averaged over the 1000-hour operating interval for each fuel injection pump.

Table 6. 30/70 ATJ/F-24 with 24-ppm CI/LI Pump Operating Summary

Parameter	Unit	Averages	Std. Dev.
Pump Speed	RPM	1700	1
Fuel Inlet Pressure	psig	3.04	0.09
Fuel Inlet Temperature	^{0}C	39.9	0.6
Housing Pressure, SN:17200072	psig	11.08	0.19
Housing Pressure, SN:17200858	psig	12.20	0.36
Transfer Pump Pressure, SN:17200072	psig	79.71	2.72
Transfer Pump Pressure, SN:17200858	psig	81.19	2.47
Pump Fuel Return Temperature, SN:17200072	^{0}C	49.8	1.1
Pump Fuel Return Temperature, SN:17200858	^{0}C	49.2	1.0
Injected Flow Rate, SN:17200072	mL/min	824.9	25.2
Injected Flow Rate, SN:17200858	mL/min	839.3	24.9

The flow histories of the fuel injection pumps operating on the ATJ/F-24 blend with 24-ppm CI/LI at 40 °C fuel inlet temperature, are shown in Figure 9. From the onset of testing both fuel injection

pumps exhibited a slight decrease in fuel delivery, followed by a steady delivery decline, then a rapid delivery recovery. Pump SN:17200858 increased injected delivery fairly steadily till the end of operation after the rapid delivery recovery. Pump SN:17200072 exhibited fairly steady after the delivery recovery, then a slight decline during the last several hundreds of hours of testing. Pump drive speed was very consistent throughout testing indicating wear was not occurring in the governor or drive tang sections of the pump. However both fuel injection pumps appeared to be functioning on the ATJ/F-24 blend with 24-ppm CI/LI at the conclusion of the 1000-hours of operation at 40 ºC fuel inlet temperature.

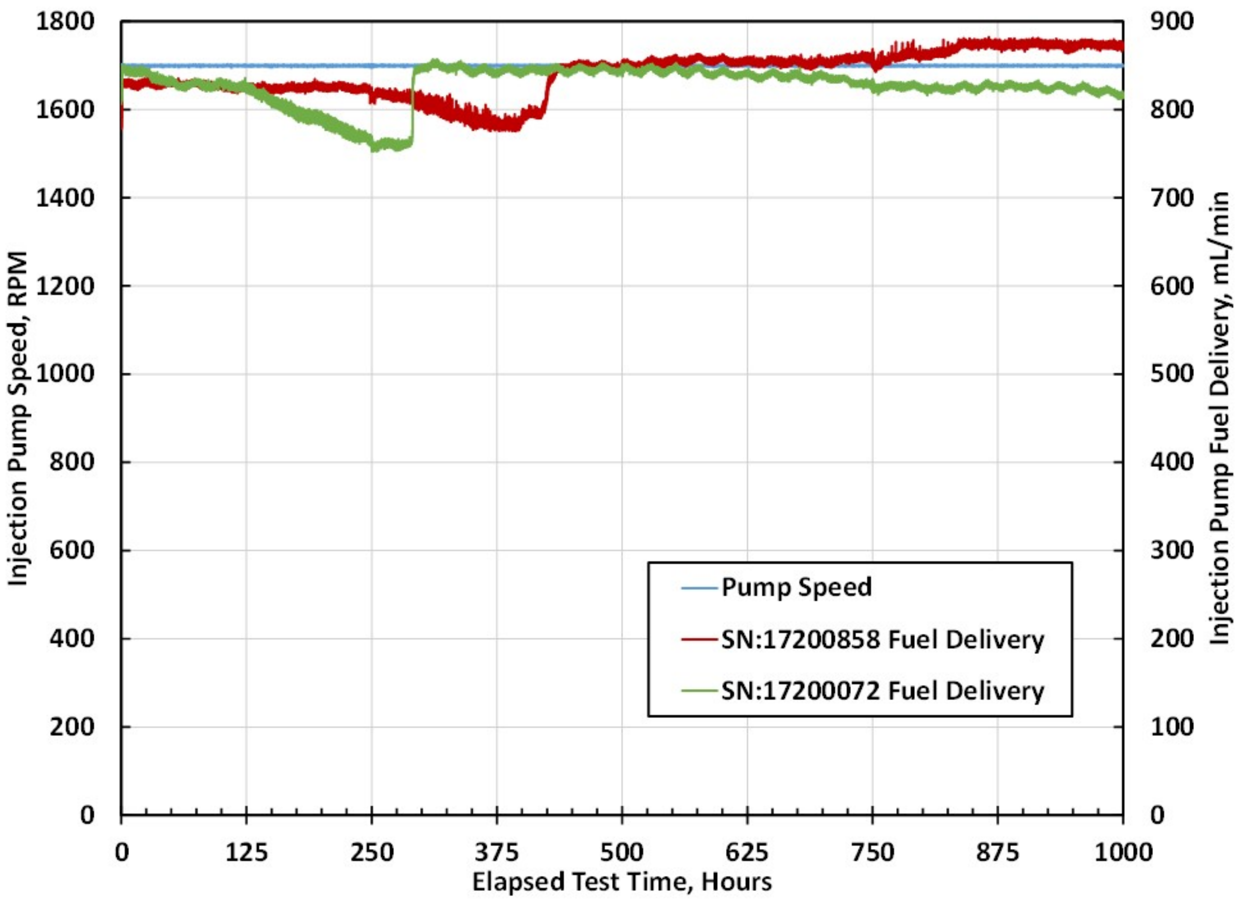


Figure 9. Injection Pump Delivery Histories for 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel Evaluation at 40 ºC

The temperature histories of the fuel injection pumps are shown in Figure 10. From the onset of testing both fuel injection pumps exhibited some form of erratic fuel return temperature behavior. For pump SN:17200072 the return fuel temperature increased, usually a sign of increased internal

friction, then decreased gradually towards end of testing. Pump SN:17200858 exhibited steady initial fuel return temperature that increased until before mid-test, then gradually decreased towards test conclusion. Unusual wear in the pumps usually result in increases and variability of the fuel return temperatures. The fuel inlet temperature to both pumps was very consistent throughout testing.

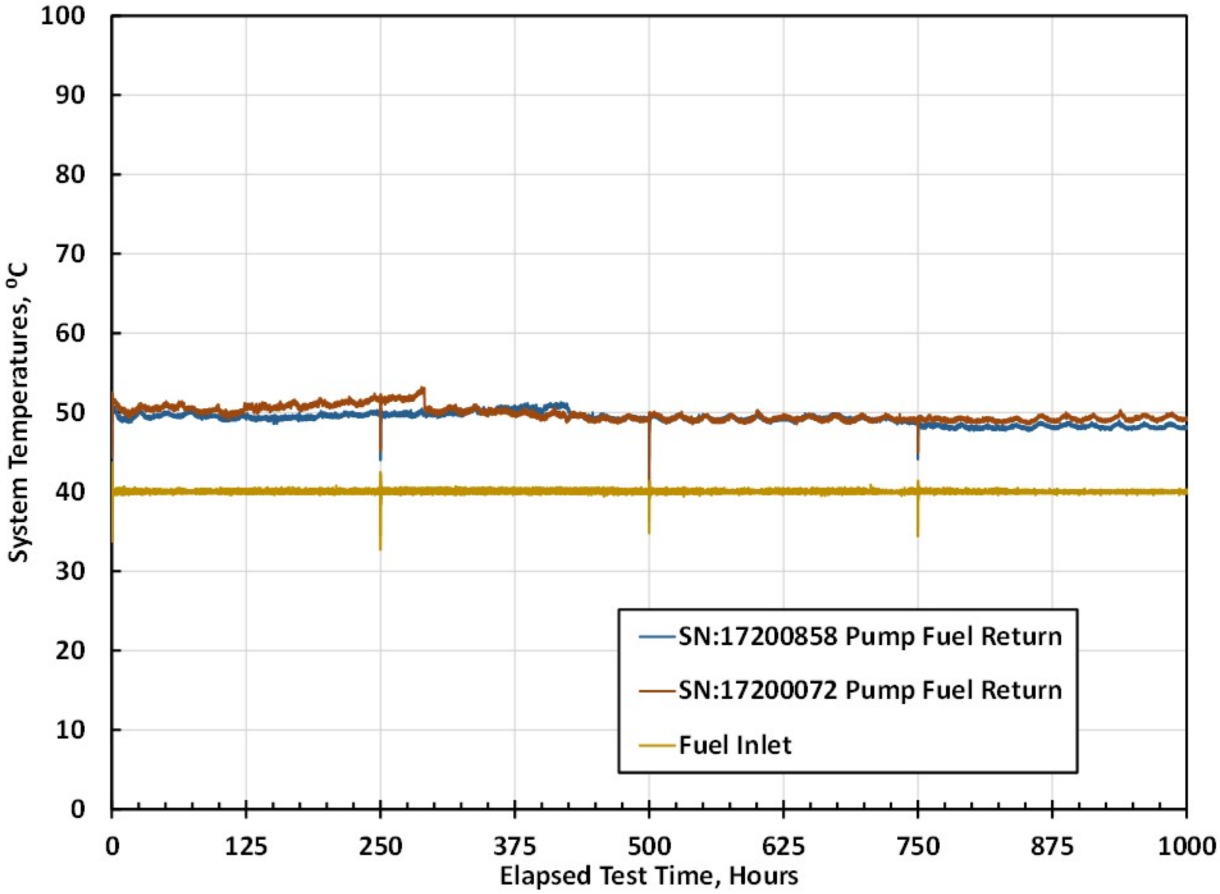


Figure 10. Injection Pump Temperature Histories for 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel Evaluation at 40 °C

Figure 11 shows the fuel pressure histories for the test with the ATJ/F-24 fuel with 24-ppm CI/LI. The fuel inlet pressure for pumps SN:17200072 and SN:17200858 maintained a consistent level throughout the 1000-hours of operation. Housing pressures for pump SN:17200072 was steady throughout testing. Housing pressure for pump SN:17200858 maintained a steady increase till 500-hours then slowly declined towards the end of the test duration. Housing pressures increase due to leakage from the high pressure section of the pump. The transfer pump pressure for pump SN:17200072 revealed a steady

increase in pressure for the first 150-hours, exhibited a sharp increase until 300-hours, followed by significant pressure drop to start of test levels, then a fairly steady value towards the end of the test. Pump SN:17200858 reveals a more gradual increase in transfer pump pressure, then a sudden decrease at 425-hours, then consistent pressure until test termination. The erratic pressure excursions of the transfer pump indicate pump liner, pump blade, and pump regulator wear. The transfer pump deviations mirrored the fuel delivery variations witnessed, suggesting wear was also occurring in the fuel metering and governing sections of the pumps.

At 1000-hours of testing the tops of both fuel injection pumps were removed for inspection of wear debris. The housing for pump SN:17200072 is shown in Figure 12 and there is light wear debris and minimal housing staining evident. The housing for pump SN:17200858 is shown in Figure 13, for which wear debris is evident along with light amber staining of the housing.

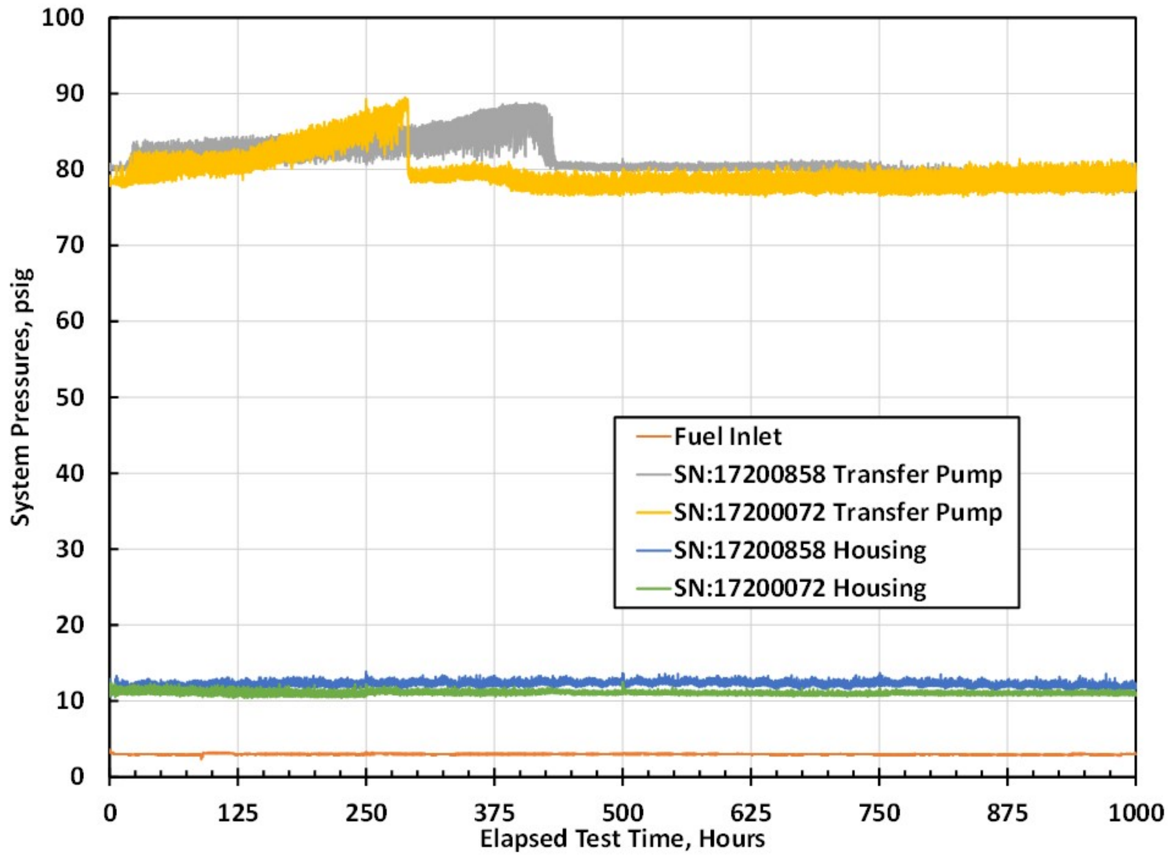


Figure 11. Injection Pump Pressure Histories for 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel Evaluation at 40 ºC

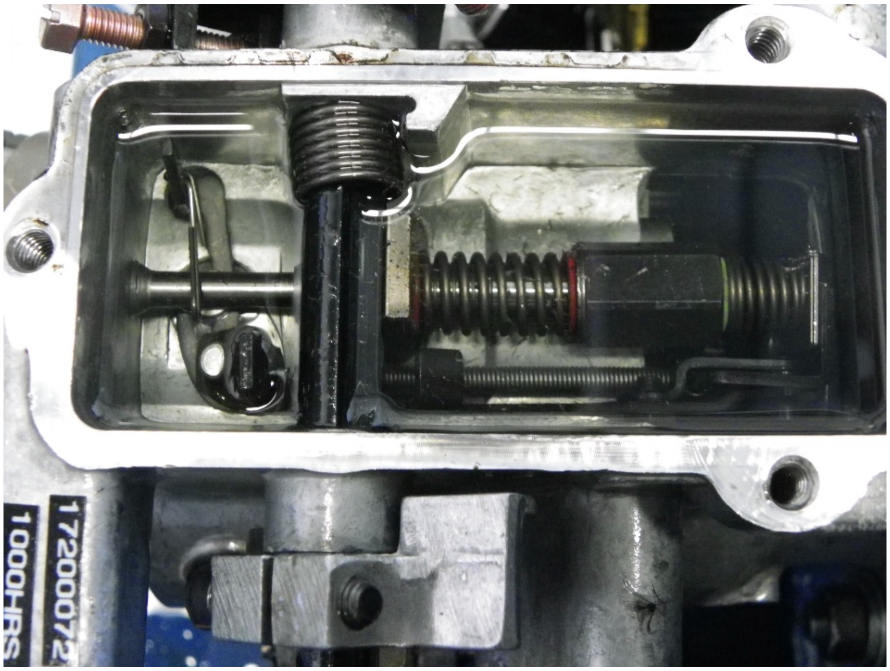


Figure 12. Pump SN:17200072 Governor Assembly with 1000-Hours Testing with 30%ATJ/F-24 Fuel at 40 ºC

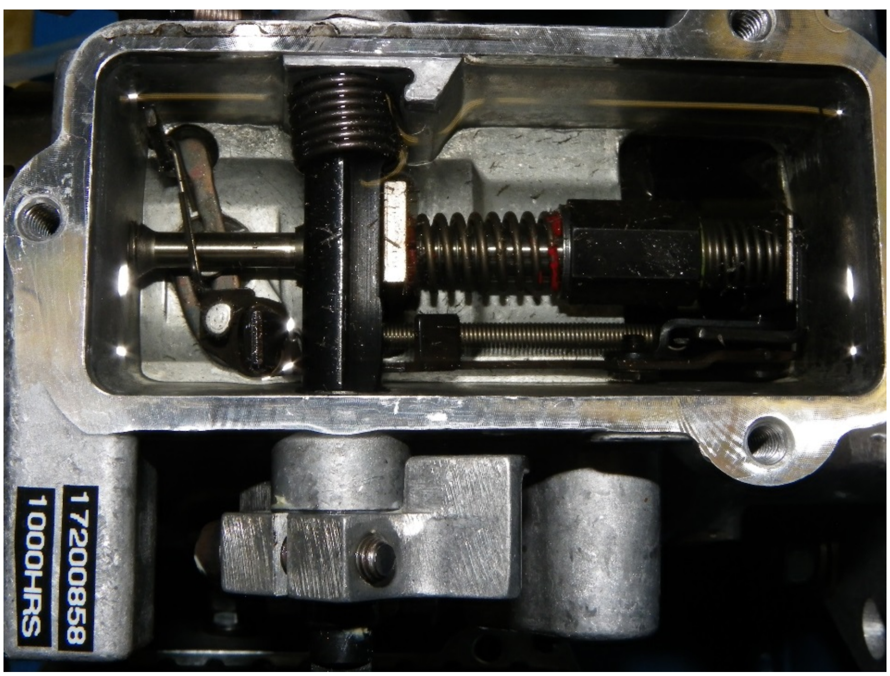


Figure 13. Pump SN:17200858 Governor Assembly with 1000-Hours Testing with 30%ATJ/F-24 Fuel at 40 ºC

5.3 ROTARY PUMP PERFORMANCE MEASUREMENTS

Prior to the durability testing all the fuel injection pumps were run on an injection pump calibration stand to verify their performance with respect to their model number and application specification sheet. Although the pumps came from the factory set to meet their designated specification, because SwRI disassembles the pumps to take transfer pump blade measurements and roller-to-roller dimensions the fuel injection pumps performance is validated by this pre-test calibration. At the conclusion of testing the fuel injection pumps were installed on the calibration stand and checked for performance changes due to the test fuel. There were not any adjustments made to the fuel injection pumps by the calibration personnel nor was the pump disassembled prior to completion of this calibration.

5.3.1 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 °C

The Pre- and Post-Test performance curves for fuel injection pump SN:17200043 are included as Table 7. Bold items in boxes in Table 7 are values that fall outside of the specification for the fuel injection pump model. Red bolding is for values below the specification minimums, blue bolding for values above the specification maximums. At the start of testing all parameters were within specifications. The end of testing specification check results indicated the fuel injection pump was over fueling at idle with slightly less advance. Idle over fueling would result in a fast idle. At 900-rpm, the engine application peak torque speed, over fueling was also evident. This would result in an increased peak torque. At 1600-rpm, close to peak power, the face cam advance was just slightly greater, by 0.25º, than the specification maximum.

The Pre- and Post-Test performance curves for fuel injection pump SN:17200045 are included as Table 8. At the start of testing, all parameters were within specifications. Post-test specification check revealed a slight increase in transfer pump pressure at 1000-rpm. The higher transfer pump pressure is indicative of lower injected delivery as evidenced by the higher return fuel flow at 1000-rpm. The substantial increase in high idle delivery at 1975-rpm indicates the governor action of the fuel injection pump was compromised. The technician checking the pump noted improper driveshaft sealing during the initial checks, however the seals started working and the checks were completed satisfactorily.

Both pumps experienced operational issues as a result of operation with the 30% ATJ/F-24 fuel with 24-ppm CI/LI at the elevated 77 °C fuel inlet temperature. The compromised governor action of pump SN:17200045 being more serious than the idle/peak torque over fueling of pump SN:17200043. It can be concluded that the 24-ppm CI/LI additive treatment of the 30/70 ATJ/F-24 fuel had marginal lubricity for rotary fuel injection pump operation at elevated temperature. This contrasts with earlier testing where a 25% ATJ blend had more serious operational issues at elevated temperatures and 24-ppm CI/LI [2]. The increased viscosity from the additional 5% ATJ in the blend appeared to be beneficial for the pumps at elevated temperature.

Table 7. Injection Pump SN:17200043 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-6282 (arctic)	SN : 17200043
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	Test : AF9625-24-C3ATJ3-77-1000
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

PUMP RPM	Description	Specification		Pump Duration: 1000 Hours		
		min.	max.	Before	After	Change
1000	Transfer pump psi.	60 psi	62 psi	60 psi	60 psi	psi
	Return Fuel	225 cc	375 cc	294 cc	228 cc	66 cc
350	Low Idle	12 cc	16 cc	14.4 cc	18.5 cc	-4.1 cc
	Housing psi.	8 psi	12 psi	10.7 psi	11.0 psi	-.3 psi
	Advance	3.5°		6.0°	5.3°	.8°
	Cold Advance Solenoid	0 psi	1 psi	.7 psi	1.1 psi	-.4 psi
750	Shut-Off		4 cc	0 cc	0 cc	0 cc
900	Fuel Delivery	64.5 cc	67.5 cc	66.0 cc	69.2 cc	-3.2 cc
1600	WOT Fuel delivery	58.5 cc		61.5 cc	65.2 cc	-3.7 cc
	WOT Advance	2.5°	3.5°	3.5°	3.5°	.0°
	Face Cam Fuel delivery	21.5 cc	23.5 cc	22.5 cc	22.5 cc	.0 cc
	Face Cam Advance	5.25°	7.25°	7.0°	7.5°	-.5°
	Low Idle	11.0°	12.0°	11.0°	11.0°	.0°
1700	WOT Fuel Delivery	58 cc		60.20 cc	62.80 cc	-2.6 cc
1850	Fuel Delivery	33 cc		42.6 cc	58.3 cc	-15.7 cc
1975	High Idle		15 cc	4 cc	13 cc	9 cc
	Transfer pump psi.		125 psi	100 psi	98 psi	1.6 psi
200	WOT Fuel Delivery	58 cc		58.0 cc	61.3 cc	-3.3 cc
	WOT Shut-Off		4 cc	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	37 cc		44.9 cc	47.9 cc	-3.0 cc
	Transfer pump psi.	16 psi		17.8 psi	18.0 psi	-.2 psi
	Housing psi.	0 psi	12 psi	10.1 psi	10.5 psi	-.4 psi
	Air Timing	-1.0°	0°	-.5°	-.8°	.3°
	Fluid Temp. Deg. C :			45.1°	45.0°	
	Date :			2/1/2017	3/31/2017	

Notes :

Table 8. Injection Pump SN:17200045 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-6282 (arctic)		SN : 17200045
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	Test : AF9625-24-C3ATJ3-77-1000	
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A		

PUMP RPM	Description	Specification		Pump Duration: 1000 Hours		
		min.	max.	Before	After	Change
1000	Transfer pump psi.	60 psi	62 psi	62 psi	63 psi	-1 psi
	Return Fuel	225 cc	375 cc	258 cc	302 cc	44 cc
350	Low Idle	12 cc	16 cc	14.0 cc	15.4 cc	-1.4 cc
	Housing psi.	8 psi	12 psi	10.6 psi	10.7 psi	-.1 psi
	Advance	3.5°		4.8°	4.5°	.3°
	Cold Advance Solenoid	0 psi	1 psi	.1 psi	.7 psi	-.6 psi
750	Shut-Off		4 cc	0 cc	0 cc	0 cc
900	Fuel Delivery	64.5 cc	67.5 cc	67.4 cc	66.7 cc	.7 cc
1600	WOT Fuel delivery	58.5 cc		61.6 cc	61.7 cc	-.1 cc
	WOT Advance	2.5°	3.5°	3.5°	3.5°	.0°
	Face Cam Fuel delivery	21.5 cc	23.5 cc	22.5 cc	22.5 cc	.0 cc
	Face Cam Advance	5.25°	7.25°	5.5°	6.0°	-.5°
	Low Idle	11.0°	12.0°	11.0°	11.5°	-.5°
1700	WOT Fuel Delivery	58 cc		62.0 cc	61.35 cc	.6 cc
1850	Fuel Delivery	33 cc		48.1 cc	60.4 cc	-12.3 cc
1975	High Idle		15 cc	5 cc	58 cc	53 cc
	Transfer pump psi.		125 psi	106 psi	99 psi	7.5 psi
200	WOT Fuel Delivery	58 cc		59.2 cc	59.7 cc	-.5 cc
	WOT Shut-Off		4 cc	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	37 cc		46.4 cc	45.2 cc	1.2 cc
	Transfer pump psi.	16 psi		18.8 psi	19.7 psi	-.9 psi
	Housing psi.	0 psi	12 psi	10.5 psi	9.8 psi	.7 psi
	Air Timing	-1.0°	0°	-.5°	-.5°	.0°
	Fluid Temp. Deg. C :			45.0°	45.0°	
	Date :			2/1/2017	3/31/2017	

Notes : Pump was leaking from driveshaft weep hole affecting the data results until 1600 rpm when the leak stopped. Went back and re-ercorded the first 8 data points.

5.3.2 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 °C

The Pre- and Post-Test performance curves for fuel injection pump SN:17200072 are included as Table 9. Items in bold in Table 9 are values that fall outside of the specification for the fuel injection pump model. Red bolding is for values below the specification minimums, blue bolding for values above the specification maximums. At the start of testing, all parameters were within specifications. At the end of testing the 900-RPM delivery parameters was only slightly above the maximum specification. The delivery characteristics at 900-RPM would likely impact the peak torque of the engine. The results at 1975-RPM suggest the governor operation had been compromised for the SN:17200072 pump on the 30%ATJ/F-24 fuel blend with 24-ppm CI/LI. The minimum delivery value at 75-RPM was met, so engine starting with this pump would not be an issue. The air timing value indicated the base timing before the advance curve takes effect advanced slightly.

The Pre- and Post-Test performance curves for fuel injection pump SN:17200858 are included as Table 10. At the start of testing, all parameters were within specifications. At the end of testing the 350-RPM idle delivery parameters was below the minimum specification. The delivery characteristics at 350-RPM impacts the idle speed of the engine, so low idle speed or stalling could result from the low delivery. The results at 1975-RPM suggest the governor operation had been compromised for the SN:17200858 pump. The minimum delivery value at 200-RPM was not met, so engine speed run up from cranking/starting to idle with this pump could be an issue.

Both fuel injection pumps completed 1000-hours of operation at the 40 ºC fuel inlet temperature with the 30% ATJ/F-24 fuel with 24-ppm CI/LI. Both pumps exhibited some performance degradation with respect to their calibration performance criterion. The pumps would likely result in erratic engine behavior if installed in a vehicle, but not a loss of power.

Table 9. Injection Pump SN:17200072 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-6282 (arctic)	**SN : 17200072**
Test condition : 1000 hours @ FIT 40°C and 1700 RPM	**Test : AF9625-24-C3ATJ4-40-1000**
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

PUMP RPM	*Description*	*Specification*		*Pump Duration: 1000 Hours*		
		min.	*max.*	*Before*	*After*	*Change*
1000	Transfer pump psi.	60 psi	62 psi	61 psi	60 psi	1 psi
	Return Fuel	225 cc	375 cc	310 cc	348 cc	38 cc
350	Low Idle	12 cc	16 cc	15.5 cc	15.3 cc	.2 cc
	Housing psi.	8 psi	12 psi	11.0 psi	10.7 psi	.3 psi
	Advance	3.5°		6.5°	5.8°	.8°
	Cold Advance Solenoid	0 psi	1 psi	.1 psi	.7 psi	-.6 psi
750	Shut-Off		4 cc	0 cc	0 cc	0 cc
900	Fuel Delivery	64.5 cc	67.5 cc	67.4 cc	**67.8 cc**	-.4 cc
1600	WOT Fuel delivery	58.5 cc		61.4 cc	63.3 cc	-1.9 cc
	WOT Advance	2.5°	3.5°	3.5°	3.5°	.0°
	Face Cam Fuel delivery	21.5 cc	23.5 cc	22.5 cc	22.5 cc	.0 cc
	Face Cam Advance	5.25°	7.25°	6.5°	7.0°	-.5°
	Low Idle	11.0°	12.0°	11.0°	11.0°	.0°
1700	WOT Fuel Delivery	58 cc		59.0 cc	62.60 cc	-3.6 cc
1850	Fuel Delivery	33 cc		42.0 cc	60.4 cc	-18.4 cc
1975	High Idle		15 cc	12 cc	**59 cc**	47 cc
	Transfer pump psi.		125 psi	101 psi	94 psi	7.0 psi
200	WOT Fuel Delivery	58 cc		58.2 cc	61.5 cc	-3.3 cc
	WOT Shut-Off		4 cc	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	37 cc		43.1 cc	51.8 cc	-8.7 cc
	Transfer pump psi.	16 psi		17.0 psi	18.4 psi	-1.4 psi
	Housing psi.	0 psi	12 psi	10.6 psi	8.1 psi	2.5 psi
	Air Timing	-1.0°	0°	-.5°	**-1.5°**	1.0°
			Fluid Temp. Deg. C :	46.1°	45.1°	
			Date :	1/26/2017	7/18/2017	

Notes :

Table 10. Injection Pump SN:17200858 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-6282 (arctic)	SN : 17200858
Test condition : 1000 hours @ FIT 40°C and 1700 RPM	Test : AF9625-24-C3ATJ4-40-1000
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

PUMP RPM	Description	Specification		Pump Duration: 1000 Hours		
		min.	max.	Before	After	Change
1000	Transfer pump psi.	60 psi	62 psi	62 psi	62 psi	psi
	Return Fuel	225 cc	375 cc	305 cc	227 cc	78 cc
350	Low Idle	12 cc	16 cc	13.8 cc	5.3 cc	8.5 cc
	Housing psi.	8 psi	12 psi	10.3 psi	10.4 psi	-.1 psi
	Advance	3.5°		6.5°	6.3°	.3°
	Cold Advance Solenoid	0 psi	1 psi	.4 psi	.7 psi	-.3 psi
750	Shut-Off		4 cc	0 cc	0 cc	0 cc
900	Fuel Delivery	64.5 cc	67.5 cc	66.6 cc	64.8 cc	1.8 cc
1600	WOT Fuel delivery	58.5 cc		60.2 cc	59.1 cc	1.1 cc
	WOT Advance	2.5°	3.5°	3.5°	3.5°	.0°
	Face Cam Fuel delivery	21.5 cc	23.5 cc	22.5 cc	22.5 cc	.0 cc
	Face Cam Advance	5.25°	7.25°	6.0°	6.0°	.0°
	Low Idle	11.0°	12.0°	11.0°	11.0°	.0°
1700	WOT Fuel Delivery	58 cc		58.10 cc	58.40 cc	-.3 cc
1850	Fuel Delivery	33 cc		43.3 cc	57.5 cc	-14.2 cc
1975	High Idle		15 cc	4 cc	54 cc	50 cc
	Transfer pump psi.		125 psi	102 psi	98 psi	3.5 psi
200	WOT Fuel Delivery	58 cc		58.2 cc	55.8 cc	2.4 cc
	WOT Shut-Off		4 cc	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	37 cc		45.9 cc	42.7 cc	3.2 cc
	Transfer pump psi.	16 psi		17.1 psi	17.8 psi	-.7 psi
	Housing psi.	0 psi	12 psi	9.7 psi	6.1 psi	3.6 psi
	Air Timing	-1.0°	0°	-.5°	-1.0°	.5°
			Fluid Temp. Deg. C :	45.5°	45.4°	
			Date :	2/20/2017	7/18/2017	

Notes :

5.4 ROTARY PUMP WEAR MEASUREMENTS

The transfer pump and plunger assemblies are integral to the fuel-metering system in the Stanadyne rotary pump, and by function are the most affected by low lubricity fuel. Accelerated wear in either the transfer pump blades or the roller-to-roller dimension results in a change of fueling condition that jeopardizes the quantity of fuel injected into the hydraulic head assembly. Wear in the transfer pump blades limits the amount of pressure necessary to maintain the proper amount of fuel in the chamber where opposing plungers, actuated by the rollers and cam, inject the metered fuel into the hydraulic head assembly. Roller-to-roller dimension variations alter the travel distance of the plungers, effectively changing metered fuel, injection pressure, and injection timing.

5.4.1 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 °C

Table 11 and Table 12 present the transfer pump blade and roller-to-roller dimension measurement results for the two fuel injection pumps that operated on 30% ATJ/F-24 fuel with 24-ppm CI/LI at elevated temperature. For pump SN:17200043 two blades started testing at the minimum length C dimension. Pump SN:17200045 had one blade start testing at the minimum length C dimension. There were three out-of-specification transfer blade measurements based on the dimension length C for both pump SN:17200043 and pump SN:17200045 at the end of testing. The width of the blades did not change dramatically, nor did the blade’s thicknesses decrease substantially. The pump roller-to-roller dimension change for both pump SN:17200043 and pump SN:17200045 was less than the ± 0.127-mm assembly specification tolerance. However the roller-to-roller dimensions did slightly increase for pump SN:17200043. The roller-to-roller eccentricity specification is 0.2032-mm maximum, which both pumps met for testing with the ATJ/F-24 fuel with 24-ppm CI/LI at elevated temperature. In general all transfer pump blades were in fair condition, and the roller-to-roller dimensions changes reflect some of the pump performance changes exhibited.

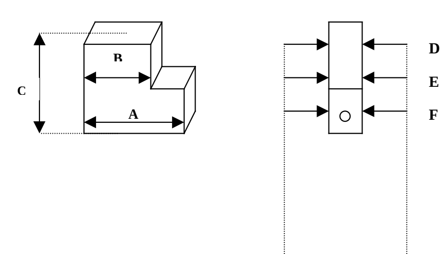
Table 11. Pump SN:17200043 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-6282	SN: 17200043	Test Number : AF9625-24-C3ATJ3-77-1000
Fuel description : AF9625 with 24ppm DCI-4A		

	Date:	11/16/2016	4/15/2017	
Dimensional Measurements (mm)		***0 hrs.***	***1000 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.7973	13.7820	-0.0152
	Dimension B	9.8971	9.8882	-0.0089
	Dimension C	12.6657	12.6619	-0.0038
	Dimension D	3.1166	3.1140	-0.0025
	Dimension E	3.1140	3.1128	-0.0013
	Dimension F	3.1166	3.1140	-0.0025
Transfer Pump Blade 2	Dimension A	13.8049	13.7897	-0.0152
	Dimension B	9.9009	9.8870	-0.0140
	Dimension C	12.6644	12.6606	-0.0038
	Dimension D	3.1217	3.1204	-0.0013
	Dimension E	3.1217	3.1204	-0.0013
	Dimension F	3.1217	3.1191	-0.0025
Transfer Pump Blade 3	Dimension A	13.8049	13.7859	-0.0191
	Dimension B	9.8971	9.8870	-0.0102
	Dimension C	12.6644	12.6594	-0.0051
	Dimension D	3.1166	3.1153	-0.0013
	Dimension E	3.1140	3.1115	-0.0025
	Dimension F	3.1153	3.1128	-0.0025
Transfer Pump Blade 4	Dimension A	13.8049	13.7897	-0.0152
	Dimension B	9.9022	9.8895	-0.0127
	Dimension C	12.6670	12.6644	-0.0025
	Dimension D	3.1217	3.1204	-0.0013
	Dimension E	3.1217	3.1191	-0.0025
	Dimension F	3.1204	3.1191	-0.0013
	Roller to Roller (mm)	50.2031	50.2412	0.0381
	Eccentricity (mm)	0.1270	0.0762	-0.0508
	Drive Backlash (mm)	0.1270	0.1778	0.0508

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

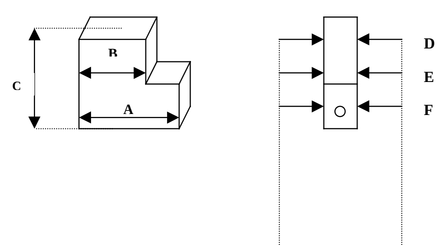
Table 12. Pump SN:17200045 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-6282	**SN: 17200045**	**Test Number : AF9625-24-C3ATJ3-77-1000**
Fuel description : AF9625 with 24ppm DCI-4A		

	Date:	11/16/2016	4/12/2017	
Dimensional Measurements (mm)		***0 hrs.***	***1000 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.7973	13.7846	-0.0127
	Dimension B	9.9593	9.9530	-0.0064
	Dimension C	12.6683	12.6670	-0.0013
	Dimension D	3.1204	3.1191	-0.0013
	Dimension E	3.1191	3.1140	-0.0051
	Dimension F	3.1191	3.1179	-0.0013
Transfer Pump Blade 2	Dimension A	13.8024	13.7947	-0.0076
	Dimension B	9.9009	9.8920	-0.0089
	Dimension C	12.6632	12.6632	0.0000
	Dimension D	3.1179	3.1128	-0.0051
	Dimension E	3.1140	3.1077	-0.0063
	Dimension F	3.1140	3.1115	-0.0025
Transfer Pump Blade 3	Dimension A	13.7986	13.7909	-0.0076
	Dimension B	9.8920	9.8819	-0.0102
	Dimension C	12.6657	12.6632	-0.0025
	Dimension D	3.1166	3.1140	-0.0025
	Dimension E	3.1166	3.1128	-0.0038
	Dimension F	3.1153	3.1128	-0.0025
Transfer Pump Blade 4	Dimension A	13.8024	13.7909	-0.0114
	Dimension B	9.8908	9.8831	-0.0076
	Dimension C	12.6657	12.6581	-0.0076
	Dimension D	3.1255	3.1242	-0.0013
	Dimension E	3.1242	3.1217	-0.0025
	Dimension F	3.1242	3.1217	-0.0025
	Roller to Roller (mm)	50.1904	50.1904	0.0000
	Eccentricity (mm)	0.1524	0.2032	0.0508
	Drive Backlash (mm)	0.2032	0.5842	0.3810

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

5.4.2 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 °C

Table 13 and Table 14 present the transfer pump blade and roller-to-roller dimension measurement results for the two fuel injection pumps that operated on the 30% ATJ/F-24 fuel blend with 24-ppm CI/LI at 40 ºC fuel inlet temperature. For pump SN:17200072 two blades started testing at the minimum length C dimension. Pump SN:17200858 also had two blades start testing at the minimum length C dimension. There were two out-of-specification transfer blade measurements based on the dimension length C for pump SN:17200072 and one blade for pump SN:17200858 at the end of testing. The width dimension A of the blades changed more than anticipated for the test temperature. The blade thicknesses did not decrease substantially for either pump. Pump SN:17200072 roller-to-roller dimensions decreased, changing less than the ±0.127-mm assembly specification tolerance and pump SN:17200858 roller-to-roller dimension increased slightly, but less than the tolerance. The roller-to-roller eccentricity specification is 0.2032-mm maximum, which neither pump SN:17200072 or SN:17200858 approached after 1000-hours testing with the 30% ATJ/F-24 fuel blend with 24-ppm CI/LI. In general all transfer pump blades were in fair condition, and the roller-to-roller dimensions changes reflected the performance changes seen on the test stand.

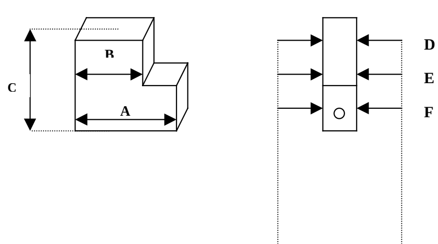
Table 13. Pump SN:17200072 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-6282	SN: 17200072	Test Number : AF9625-24-C3ATJ4-40-1000
Fuel description : 30% ATJ, AF9625 with 24ppm DCI-4A		

	Date:	1/21/2017	8/9/2017	
Dimensional Measurements (mm)		***0 hrs.***	***1000 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.8113	13.7566	-0.0546
	Dimension B	9.8958	9.8654	-0.0305
	Dimension C	12.6657	12.6657	0.0000
	Dimension D	3.1217	3.1217	0.0000
	Dimension E	3.1191	3.1191	0.0000
	Dimension F	3.1204	3.1204	0.0000
Transfer Pump Blade 2	Dimension A	13.7935	13.7541	-0.0394
	Dimension B	9.9212	9.9022	-0.0191
	Dimension C	12.6606	12.6606	0.0000
	Dimension D	3.1229	3.1229	0.0000
	Dimension E	3.1204	3.1204	0.0000
	Dimension F	3.1217	3.1217	0.0000
Transfer Pump Blade 3	Dimension A	13.8049	13.7592	-0.0457
	Dimension B	9.8984	9.8692	-0.0292
	Dimension C	12.6644	12.6644	0.0000
	Dimension D	3.1242	3.1229	-0.0013
	Dimension E	3.1204	3.1204	0.0000
	Dimension F	3.1229	3.1229	0.0000
Transfer Pump Blade 4	Dimension A	13.7998	13.7617	-0.0381
	Dimension B	9.9238	9.9047	-0.0190
	Dimension C	12.6619	12.6619	0.0000
	Dimension D	3.1229	3.1229	0.0000
	Dimension E	3.1191	3.1191	0.0000
	Dimension F	3.1229	3.1229	0.0000
	Roller to Roller (mm)	50.1396	50.1142	-0.0254
	Eccentricity (mm)	0.0254	0.0508	0.0254
	Drive Backlash (mm)	0.1524	0.5080	0.3556

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

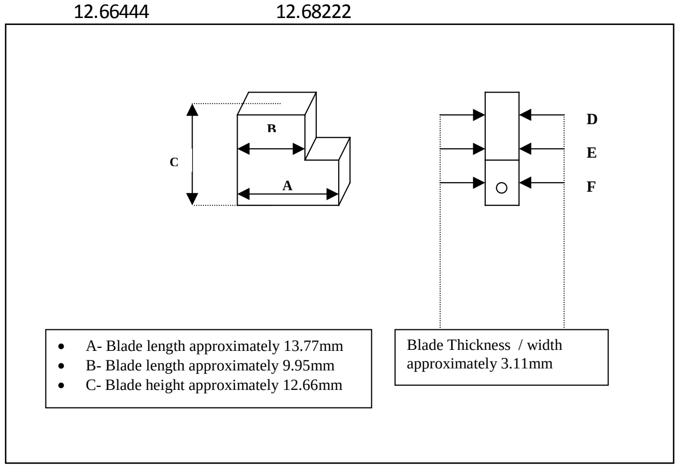
Table 14. Pump SN:17200858 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-6282	SN: 17200858	Test Number : AF9625-24-C3ATJ4-40-1000
Fuel description : 30% ATJ, AF9625 with 24ppm DCI-4A		

	Date:	1/21/2017	8/9/2017	
Dimensional Measurements (mm)		***0 hrs.***	***1000 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.7973	13.7668	-0.0305
	Dimension B	9.8997	9.8679	-0.0317
	Dimension C	12.6670	12.6657	-0.0013
	Dimension D	3.1204	3.1191	-0.0013
	Dimension E	3.1204	3.1191	-0.0013
	Dimension F	3.1204	3.1204	0.0000
Transfer Pump Blade 2	Dimension A	13.8049	13.7884	-0.0165
	Dimension B	9.8997	9.8857	-0.0140
	Dimension C	12.6644	12.6632	-0.0013
	Dimension D	3.1179	3.1179	0.0000
	Dimension E	3.1166	3.1166	0.0000
	Dimension F	3.1179	3.1179	0.0000
Transfer Pump Blade 3	Dimension A	13.8011	13.7668	-0.0343
	Dimension B	9.9251	9.9060	-0.0190
	Dimension C	12.6695	12.6695	0.0000
	Dimension D	3.1217	3.1217	0.0000
	Dimension E	3.1217	3.1204	-0.0013
	Dimension F	3.1217	3.1217	0.0000
Transfer Pump Blade 4	Dimension A	13.8049	13.7478	-0.0571
	Dimension B	9.8997	9.8616	-0.0381
	Dimension C	12.6644	12.6644	0.0000
	Dimension D	3.1204	3.1204	0.0000
	Dimension E	3.1191	3.1179	-0.0013
	Dimension F	3.1191	3.1191	0.0000
	Roller to Roller (mm)	50.1853	50.2412	0.0559
	Eccentricity (mm)	0.0127	0.0762	0.0635
	Drive Backlash (mm)	0.1270	0.5334	0.4064

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



5.5 FUEL INJECTOR RESULTS

Fuel injector nozzle tests were performed in accordance with procedures set forth in an approved 6.5LT diesel engine manual using diesel nozzle tester J 29075B. Nozzle testing is comprised of the following checks:

- Nozzle Opening Pressure
- Leakage
- Chatter
- Spray Pattern

Each test is considered independent of the others, and if any one of the tests is not satisfied, the injector should be replaced.

The normal opening pressure specification for these injectors is 1500 psig minimum. The specified nozzle leakage test involves pressurizing the injector nozzle to 1400 psig and holding for 10 seconds – no fuel droplets should separate from the injector tip. The chatter and spray pattern evaluations are subjective. A sharp audible chatter from the injector and a finely misted spray cone are required.

New Bosch Model O432217276 injectors were used for both of the fuels tests. The injector performance tests and rating results are shown in Table 15 for the ATJ/F-24 test with 24-ppm CI/LI at 77 ºC fuel inlet temperature. All sixteen fuel injectors passed the post-test opening pressure evaluations after the 1000-hour testing interval. All sixteen fuel injectors passed the injector tip leakage test. Fifteen of the sixteen fuel injectors passed the chatter evaluation. Fourteen of the sixteen fuel injectors passed the spray pattern checks.

The injector performance tests and rating results are shown in Table 16 for the 40 ºC fuel inlet temperature 30% ATJ/F-24 fuel with 24-ppm CI/LI test. Only eleven of sixteen fuel injectors met the minimum nozzle opening pressure after 1000-hours of operation. Only ten of sixteen fuel injectors passed the injector tip leakage evaluation. Interestingly all sixteen fuel injectors passed both the chatter and the spray pattern evaluations after 1000-hours of operation.

Table 15. Fuel Injector Performance Evaluations after 1000-Hours ATJ/F-24 with 24-ppm CI/LI Fuel Usage at 77 ºC

Stanadyne Rotary Pump Lubricity Evaluation

6.5L Fuel Injector Test Inspection

Test No.	Inj. Pump ID No.	Fuel	Inj. ID No.	Opening Pressure (pre-test)	Opening Pressure (post-test)	Tip Leakage (pre-test)	Tip Leakage (post-test)	Chatter (pre-test)	Chatter (post-test)	Spray pattern (pre-test)	Spray pattern (post-test)	Date (pre-test)	Date (post-test)	Test Hours	Tech.
AF9625-24-C3ATJ3-77-1000	SN : 17200043	30% ATJ, AF9625 with 24ppm DCI-4A	ATJ3-1	2200	1900	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-2	2125	1750	pass	fail	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-3	2150	1900	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-4	2250	1925	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-5	2150	1700	pass	pass	pass	fail	pass	fail	12/14/2016	3/31/2017	1000	REG
			ATJ3-6	2100	1800	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-7	2125	1875	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-8	2200	1875	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
AF9625-24-C3ATJ3-77-1000	SN : 17200045	30% ATJ, AF9625 with 24ppm DCI-4A	ATJ3-9	2200	1875	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-10	2200	1825	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-11	2200	1875	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-12	2100	1775	pass	pass	pass	pass	pass	fail	12/14/2016	3/31/2017	1000	REG
			ATJ3-13	2175	1775	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-14	2100	1725	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-15	2075	1800	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			ATJ3-16	2100	1775	pass	pass	pass	pass	pass	pass	12/14/2016	3/31/2017	1000	REG
			Spec. :	1500psig min	1500psig min	no drop off in 10 sec. @ 1400 psi	no drop off in 10 sec. @ 1400 psi	chatter	chatter	fine mist	fine mist				

Comments :

Table 16. Fuel Injector Performance Evaluations after 1000-Hours ATJ/F-24 with 24-ppm CI/LI Fuel Usage at 40 ºC

Stanadyne Rotary Pump Lubricity Evaluation

6.5L Fuel Injector Test Inspection

Test No.	Inj. Pump ID No.	Fuel	Inj. ID No.	Opening Pressure (pre-test)	Opening Pressure (post-test)	Tip Leakage (pre-test)	Tip Leakage (post-test)	Chatter (pre-test)	Chatter (post-test)	Spray pattern (pre-test)	Spray pattern (post-test)	Date (pre-test)	Date (post-test)	Test Hours	Tech.
AF9625-24-C3ATJ4-40-1000	SN : 17200072	30% ATJ, AF9625 with 24ppm DCI-4A	ATJ4-1	2125	1490	pass	NA/Fail*	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-2	2175	1550	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-3	2200	1475	pass	NA/Fail	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-4	2200	1550	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-5	2200	1500	pass	NA/Fail	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-6	2125	1450	pass	NA/Fail	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-7	2150	1400	pass	NA/Fail	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-8	2175	1725	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
AF9625-24-C3ATJ4-40-1000	SN : 17200858	30% ATJ, AF9625 with 24ppm DCI-4A	ATJ4-9	2125	1625	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-10	2125	1700	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-11	2150	1625	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-12	2100	1600	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-13	2225	1525	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-14	2175	1700	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-15	2125	1625	pass	pass	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			ATJ4-16	2175	1425	pass	NA/Fail	pass	pass	pass	pass	12/15/2016	7/7/2017	1000	REG
			Spec. :	1500psig min	1500psig min	no drop off in 10 sec. @ 1400 psi	no drop off in 10 sec. @ 1400 psi	chatter	chatter	fine mist	fine mist				

Comments : NA/Fail* indicates Nozzle Opening Pressure reduction was sufficiently close to the Tip Leakage test pressure that tip leakage could not be differentiated from the start of injection.

5.6 ROTARY PUMP COMPONENT WEAR EVALUATIONS

After the fuel injection pump calibration and functional performance checks, the fuel injection pumps were disassembled and the components critical to pump operation were evaluated for parts conditions. A technician with over twenty-five years of experience rebuilding, servicing, and testing Stanadyne fuel injection pumps performed the subjective wear ratings.

5.6.1 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 °C – Pump SN:17200043

The parts conditions and subjective wear ratings for fuel injection pump SN:17200043 are summarized in Table 17. Images of the wear seen on the components of fuel injection pump SN:17200043 are shown in Figure 14 through Figure 33. Figure 14 and Figure 15 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 14 and Figure 15 reveal very light distress at the rotor discharge ports, evidenced by a very light circumferential scratch.

The driveshaft seal deposition shown in Figure 16 is very unusual for the 1000-hours of pump operation. The two left seals are for keeping fuel in the housing, the rightmost seal is for keeping engine oil out of the pump. The governor fork shown in Figure 17 reveals wear on the fork tines and on the thermal compensation tab. The tab is a bimetallic material that provides some governor compensation from thermal deviations.

Figure 18 and Figure 19 are the Pre-Test and Post-Test conditions of the fuel injection pump SN:17200043 roller shoe and roller conditions. Of note is the lack of any wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 18. Figure 19 reveals a wear scar on the roller shoe from the leaf spring contact, moderate burnishing of the rollers, and little evidence of pitting and scoring of the rollers. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure 20 and Figure 21 show the roller shoe plunger contact regions, with a moderate wear scar on one shoe, and a heavy scar on the other, due to 1000-hours operation.

Table 17. Pump SN:17200043 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-6282	SN : 17200043
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	TEST : AF9625-24-C3ATJ3-77-1000
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Brown deposits. Wear from liner & regulator contact	2.5
BLADE SPRINGS	Rubbing wear	1.5
LINER	Brown deposits. Wear from blades. 90% surface wear	3
TRANSFER PUMP REGULATOR	Brown deposits. Wear scar from rotor & blades	2
REGULATOR PISTON	Polishing wear	2
ROTOR	Wear marks at inlet ports	2.5
ROTOR RETAINERS	Brown deposits. Wear from rotor contact	2.5
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Left plunger worn more than the right. Some discoloration	2.5
SHOES	Dimple from plungers. Wear from leaf spring. Scratching from rollers. Wear from rotor slots	3.5
ROLLERS	discolored & light scoring	2.5
LEAF SPRING	wear from shoes	2.5
CAM RING	Polishing wear	2
THRUST WASHER	Polishing wear on both sides from weights & sleeve.	2
THRUST SLEEVE	Worn from linkage fingers	2.5
GOVERNOR WEIGHTS	Worn at heal & thrust washer contact	2.5
LINK HOOK	Dimple from governor rod. Worn fingers & pivot	2.5
METERING VAVLE	Brown deposits. Wear along helix	2.5
DRIVE SHAFT TANG	Light polishing wear	1
DRIVE SHAFT SEALS	Dried grease caked on seals	2
CAM PIN	Polishing wear	1.5
ADVANCE PISTON	Polishing & fretting wear. Brown deposits	2.5
HOUSING	Light golden brown deposits near governor weights	1.5
AVERAGE DEMERIT RATINGS		2.24

The injection pump cam ring shown in Figure 22 and Figure 23 reveals moderate distress, with evidence of sliding contact, and moderate lobe wear from 1000-hours of operation with the 30%

ATJ/F-24 fuel with 24-ppm CI/LI at elevated temperature. The level cam lobe wear is consistent with the wear seen on the rollers.

The governor thrust washer condition before and after 1000-hours are shown in Figure 24 and Figure 25. The polishing wear seen on the thrust washer in Figure 25 seems lighter than normal for 1000-hours of injection pump operation. Light polishing seen on the advance piston suggests low fluctuating fuel pressures in that area of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The wear on these components is normal considering the 1000-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve may have affected fuel injection pump operation.

Figure 26 and Figure 27 illustrate the level of wear seen in the transfer pump section of fuel injection pump SN:17200043. Figure 26 shows the surface condition of the transfer pump liner prior to testing and Figure 27 shows the surface with scarring seen on 90% of the area after 1000-hours of operation on the ATJ/F-24 fuel with 24-ppm CI/LI at elevated temperature. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure 28 through Figure 31. The edge wear shown in Figure 28 and Figure 29 corresponds to the surface on the transfer pump blades that contact and slide on the transfer pump liner, separated by a film of fuel. The blade edge conditions in Figure 29 reflect the wear seen on the transfer pump liner. The side polishing shown in Figure 30 and Figure 31 reflect wear from the transfer pump blade slots on the injection pump rotor, and is relatively mild with some fuel deposition. The wear seen on the transfer pump components seems consistent with the 1000-hour testing duration for pump SN:17200043.

Figure 32 and Figure 33 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 32 and Figure 33 reveal only minor wear scars that indicates backlash and timing were not affected with the ATJ/F-24 fuel with 24-ppm CI/LI at elevated temperature after 1000-hours.

Figure 14. Pump SN:17200043 Distributor Rotor before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 15. Pump SN:17200043 Distributor Rotor with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 16. Pump SN:17200043 Driveshaft Seal Deposits with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 17. Pump SN:17200043 Governor Fork Wear on Tines and Tab with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 18. Pump SN:17200043 Rollers and Shoe before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 19. Pump SN:17200043 Rollers and Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 20. Pump SN:17200043 Roller Shoe before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 21. Pump SN:17200043 Roller Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

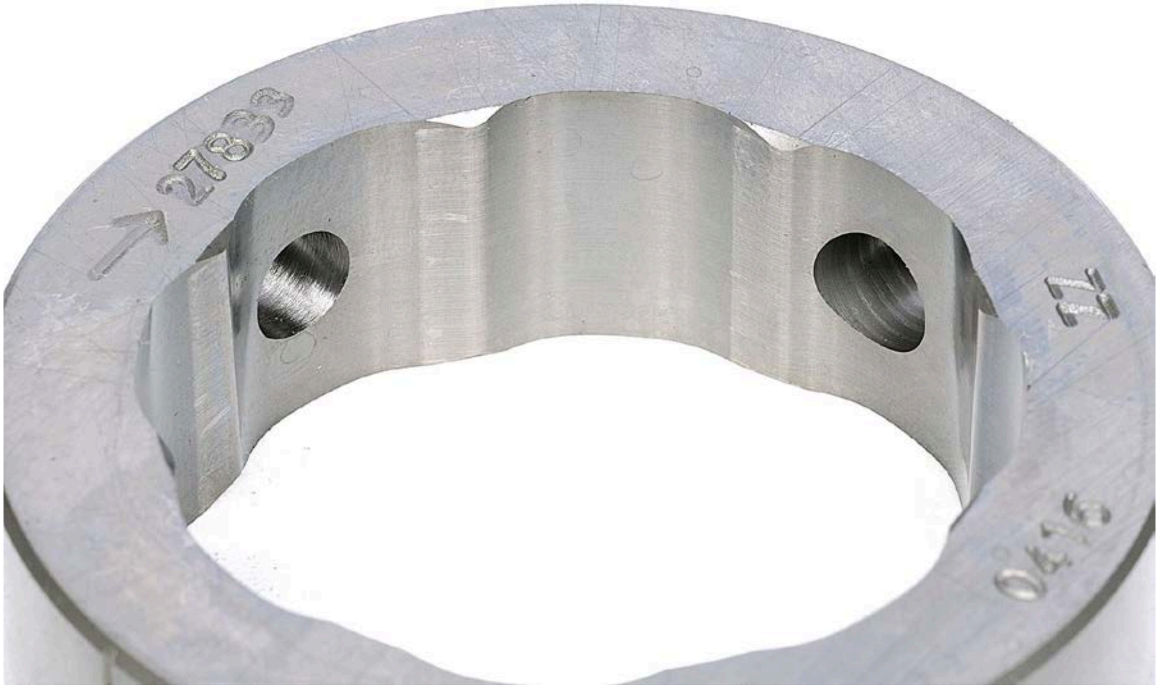


Figure 22. Pump SN:17200043 Cam Ring before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 23. Pump SN:17200043 Cam Ring with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 24. Pump SN:17200043 Thrust Washer before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 25. Pump SN:17200043 Thrust Washer with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 26. Pump SN:17200043 Transfer Pump Liner before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 27. Pump SN:17200043 Transfer Pump Liner with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 28. Pump SN:17200043 Transfer Pump Blade Edges before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 29. Pump SN:17200043 Transfer Pump Blade Edges with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 30. Pump SN:17200043 Transfer Pump Blade Sides before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 31. Pump SN:17200043 Transfer Pump Blade Sides with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 32. Pump SN:17200043 Driveshaft Drive Tang before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 33. Pump SN:17200043 Driveshaft Drive Tang with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

5.6.2 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 °C – Pump SN:17200045

The parts conditions and subjective wear ratings for fuel injection pump SN:17200045 are summarized in Table 18. Images of the wear seen on the components of fuel injection pump SN:17200045 are shown in Figure 34 through Figure 53. Figure 34 and Figure 35 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 35 reveal the circumferential light scratches at the rotor discharge ports, usually from wear debris, after the 1000-hours.

The driveshaft seal deposition shown in Figure 36 is very light for the 1000-hours of pump operation. The two left seals are for keeping fuel in the housing, the rightmost seal is for keeping engine oil out of the pump. The governor fork shown in Figure 37 reveals wear on the fork tines and on the thermal compensation tab. The tab is a bimetallic material that provides some governor compensation from thermal deviations.

Figure 38 and Figure 39 are the Pre-Test and Post-Test conditions of the fuel injection pump SN:17200045 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 38. Figure 39 reveals only light polishing wear on the roller shoe from the leaf spring contact. Figure 39 shows the Rollers and Roller Shoes with roller discoloration due to heavy burnishing on one roller and moderate burnishing and roller scratching on the other. Figure 40 and Figure 41 show the moderate wear scars due to 1000-hours operation on the roller shoe plunger contact area. The injection pump cam ring conditions are shown in Figure 42 and Figure 43. The cam ring the rollers ride on exhibited flattened cam lobes towards the edges as seen in Figure 43, and appear to reflect the wear seen on the rollers.

The governor thrust washer condition before and after 1000-hours is seen in Figure 44 and Figure 45. The polishing wear seen on the thrust washer in Figure 45 is mild for 1000-hours of injection pump operation. Light polishing and fretting seen on the advance piston suggests fluctuating fuel pressure in that region of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The wear on these components appear normal for the 1000-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve likely did not affect pump operation.

Table 18. Pump SN:17200045 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-6282	**SN : 17200045**
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	**TEST : AF9625-24-C3ATJ3-77-1000**
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Brown deposits. Wear from liner & regulator contact	2.5
BLADE SPRINGS	Rubbing wear	1.5
LINER	Brown deposits. Wear from blades. 85% surface wear	3
TRANSFER PUMP REGULATOR	Brown deposits. Wear scar from rotor & blades	2.5
REGULATOR PISTON	Polishing wear	2.5
ROTOR	Heavy wear marks at inlet & distributor ports	4
ROTOR RETAINERS	Brown deposits. Wear from rotor contact	2.5
DELIVERY VALVE	Polishing wear	2.5
PLUNGERS	Discolored & heavy polishing wear	3.5
SHOES	Dimple from plungers. Light wear from leaf spring. Scratching from rollers.	2.5
ROLLERS	discolored & light scoring	2.5
LEAF SPRING	wear from shoes	2
CAM RING	Polishing wear	2
THRUST WASHER	Polishing wear on both sides from weights & sleeve	2
THRUST SLEEVE	Worn from linkage fingers & weights	2.5
GOVERNOR WEIGHTS	Worn at heal & thrust washer contact	2
LINK HOOK	Dimple from governor rod. Worn fingers & pivot. Dimple from governor spring	3.5
METERING VAVLE	Brown deposits. Wear along helix	2.5
DRIVE SHAFT TANG	Heavy wear	3
DRIVE SHAFT SEALS	Normal	1.5
CAM PIN	Polishing wear	1.5
ADVANCE PISTON	Polishing & fretting wear. Brown deposits	2.5
HOUSING	Light golden brown deposits near governor weights	1
	AVERAGE DEMERIT RATINGS	2.41

Figure 46 and Figure 47 illustrates the level of wear seen in the transfer pump section of fuel injection pump SN:17200045. Figure 46 shows the surface condition of the transfer pump liner prior to testing and Figure 47 shows the surface with 85% surface area scored after 1000-hours of operation on the elevated temperature ATJ/F-24 fuel with 24-ppm CI/LI. Also illustrative of wear in the transfer pump section are the transfer pump blade conditions shown in Figure 48 through Figure 51. The edge wear shown in Figure 48 and Figure 49 corresponds to the surface on the transfer pump blades that contact the transfer pump liner. The blade edge conditions in Figure 49 reflect the scoring seen on the transfer pump liner, and appear typical for 1000-hours operation with moderate lubricity fuel at elevated temperature. The side polishing shown in Figure 50 and Figure 51 reflect wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components seems consistent with the testing duration for pump SN:17200045.

Figure 52 and Figure 53 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Of interest is the new drive tang in Figure 52 reveals unusual surface conditions for a new part. Figure 53 reveals a moderate wear scar that indicates some backlash was occurring. For both pumps the cumulative effect of all the worn components contributed to the performance degradation with the ATJ/F-24 fuel with 24-ppm CI/LI at 77 °C fuel inlet temperature.

Figure 34. Pump SN:17200045 Distributor Rotor before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 35. Pump SN:17200045 Distributor Rotor with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 36. Pump SN:17200045 Driveshaft Seal Deposits with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 37. Pump SN:17200045 Governor Fork Wear on Tines and Tab with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 38. Pump SN:17200045 Rollers and Shoe Condition before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 39. Pump SN:17200045 Rollers and Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 40. Pump SN:17200045 Roller Shoe Condition before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 41. Pump SN:17200045 Roller Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

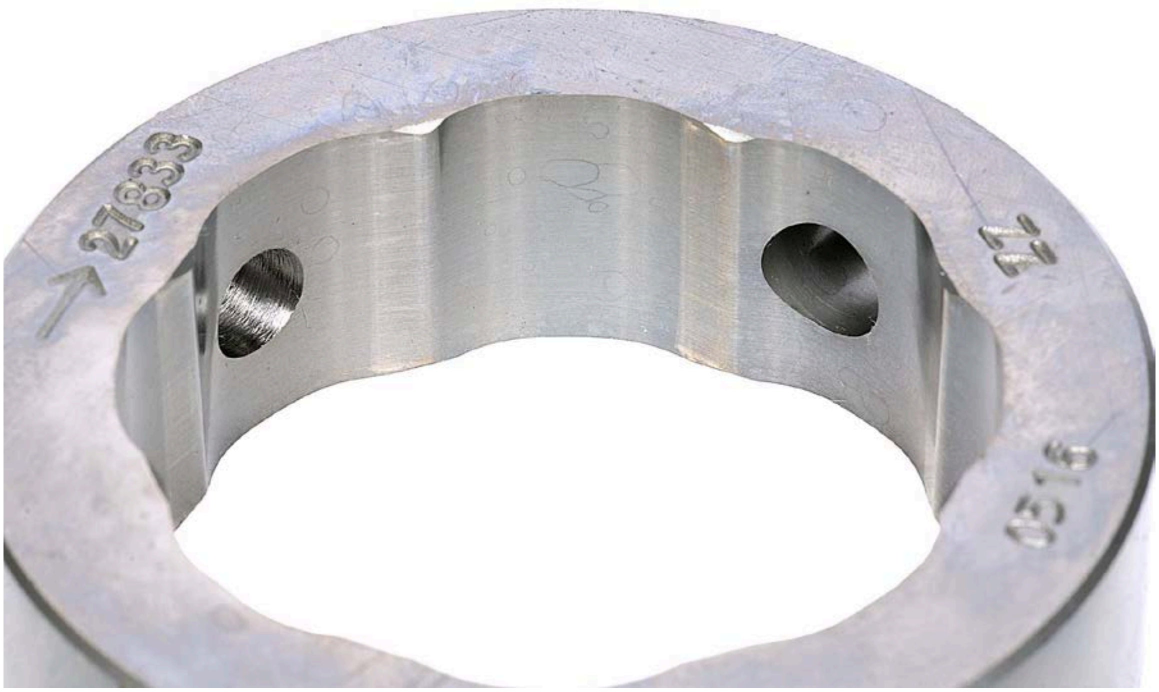


Figure 42. Pump SN:17200045 Cam Ring Before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 43. Pump SN:17200045 Cam Ring with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 44. Pump SN:17200045 Thrust Washer Before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 45. Pump SN:17200045 Thrust Washer with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 46. Pump SN:17200045 Transfer Pump Liner before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 47. Pump SN:17200045 Transfer Pump Liner with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 48. Pump SN:17200045 Transfer Pump Blade Edges before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 49. Pump SN:17200045 Transfer Pump Blade Edges with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 50. Pump SN:17200045 Transfer Pump Blade Sides before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 51. Pump SN:17200045 Transfer Pump Blade Sides with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 52. Pump SN:17200045 Driveshaft Drive Tang before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

Figure 53. Pump SN:17200045 Driveshaft Drive Tang with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 77 ºC

5.6.3 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel Blend at 40 °C – Pump SN:17200072

The parts conditions and subjective wear ratings for fuel injection pump SN:17200072 are summarized in Table 19. Images of the wear seen on the components of fuel injection pump SN:17200072 are shown in Figure 54 through Figure 71. Figure 54 and Figure 55 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 55 shows the discharge ports and rotor are in good condition, with very little distress evident after 1000-hours with ATJ/F-24 fuel with 24-ppm CI/LI at 40 ºC fuel inlet temperature.

Figure 56 and Figure 57 is the Pre-Test and Post-Test conditions of the fuel injection pump SN:17200072 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 56. Figure 57 reveals mild wear scars on the roller shoe from the leaf spring contact, light burnishing of the rollers, and no evidence of scoring on the rollers. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure 58 and Figure 59 show the relatively mild wear scars due to 1000-hours operation on the roller shoe plunger contact. The injection pump cam ring shown in Figure 60 and Figure 61 reveals light polishing on the cam lobes with the 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel blend.

The governor thrust washer condition before and after 1000-hours is seen in Figure 62 and Figure 63. The polishing wear seen on the thrust washer in Figure 63 is typical for the 1000-hour operating interval. Polishing and light fretting seen on the advance piston suggests the fuel pressure fluctuates in that area of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The light wear on these components is normal considering the 1000-hour duration of testing. The wear on the thrust washer and the advance piston wear likely did not have an effect on pump operation. The metering valve wear may have affected the governor cut-off operation.

Figure 64 and Figure 65 illustrates the level of wear seen in the transfer pump section of fuel injection pump SN:17200072. Figure 64 shows the surface condition of the transfer pump liner prior to testing and Figure 65 shows the surface with moderate 85% circumferential scarring after

1000-hours of operation on the 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure 66 through Figure 69. The edge wear shown in Figure 66 and Figure 67 corresponds to the surface on the transfer pump blades that contact the transfer pump liner, and they reveal moderate scoring. Pump SN:17200072 had a broken blade spring that could have affected transfer pump component wear. The side polishing shown in Figure 68 and Figure 69 reflect wear from the transfer pump blade slots on the injection pump rotor. The transfer pump component conditions suggest the test fuel has marginal fuel lubricity.

Figure 70 and Figure 71 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 71 reveals a wear scar that indicates minor backlash was occurring with the 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel blend after 1000-hours at elevated 40 °C fuel inlet temperature. Post-test specification checks did indicate a slight base timing change, possibly due to the drive tang wear.

Table 19. Pump SN:17200072 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-6282	SN : 17200072
Test condition : 1000 hours @ FIT 40°C and 1700 RPM	TEST : AF9625-24-C3ATJ4-40-1000
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear from liner, rotor slots & broken blade spring.	2.5
BLADE SPRINGS	One spring broken	4
LINER	85% wear from blades	3
TRANSFER PUMP REGULATOR	Wear scar from rotor & blades	2.5
REGULATOR PISTON	Polishing wear	1.5
ROTOR	rotational scarring at inlet and distributor ports	2.5
ROTOR RETAINERS	Wear from rotor	2.5
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear	2
SHOES	Dimple from plungers. Light wear from leaf spring. Scratching from rollers.	2.5
ROLLERS	Lighr wear	1.5
LEAF SPRING	wear from shoes	2.5
CAM RING	Polishing wear	2
THRUST WASHER	Polishing wear on both sides from weights & sleeve	1.5
THRUST SLEEVE	Heavy wear from linkage fingers & weights	3
GOVERNOR WEIGHTS	Wear from thrust washer	1.5
LINK HOOK	Dimple from governor rod. Worn fingers & pivot. Dimple from governor spring	3.5
METERING VAVLE	Wear along helix. Golden brown deposits	2
DRIVE SHAFT TANG	Heavy wear from rotor slot	3.5
DRIVE SHAFT SEALS	Normal	1
CAM PIN	Normal	1
ADVANCE PISTON	Polishing & fretting wear. Brown deposits	2.5
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	2.24

Figure 54. Pump SN:17200072 Distributor Rotor before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 55. Pump SN:17200072 Distributor Rotor with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 56. Pump SN:17200072 Rollers and Shoe before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 57. Pump SN:17200072 Rollers and Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 58. Pump SN:17200072 Roller Shoe before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 59. Pump SN:17200072 Roller Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 60. Pump SN:17200072 Cam Ring before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 61. Pump SN:17200072 Cam Ring with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 62. Pump SN:17200072 Thrust Washer before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 63. Pump SN:17200072 Thrust Washer with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 64. Pump SN:17200072 Transfer Pump Liner before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 65. Pump SN:17200072 Transfer Pump Liner with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 66. Pump SN:17200072 Transfer Pump Blade Edges before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 67. Pump SN:17200072 Transfer Pump Blade Edges with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 68. Pump SN:17200072 Transfer Pump Blade Sides before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 69. Pump SN:17200072 Transfer Pump Blade Sides with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 70. Pump SN:17200072 Driveshaft Drive Tang Sides before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 71. Pump SN:17200072 Driveshaft Drive Tang with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

5.6.4 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel Blend at 40 °C – Pump SN:17200858

The parts conditions and subjective wear ratings for fuel injection pump SN:17200858 are summarized in Table 20. Images of the wear seen on the components of fuel injection pump SN:17200858 are shown in Figure 72 through Figure 89. Figure 72 and Figure 73 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 73 shows the discharge ports and rotor with minimal distress on the rotor or near the rotor discharge ports after the 1000-hours of operation. The rotor conditions with the ATJ/F-24 blend with 24-ppm CI/LI at 40 ºC has less distress than the rotor conditions seen as a result of 1000-hours at the elevated 77 ºC temperature.

Figure 74 and Figure 75 is the Pre-Test and Post-Test conditions of fuel injection pump SN:17200858 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 74. Figure 75 reveals very light wear scars on the roller shoe from the leaf spring contact and light burnishing of the rollers. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure 76 and Figure 77 show the relatively moderate wear scar due to 1000-hours operation at the roller shoe plunger contact. The injection pump cam ring shown in Figure 78 and Figure 79 reveals minimal polishing and wear on the cam lobes from 1000-hours operation with the ATJ/F-24 fuel blend. The roller and cam distress with the ATJ/F-24 blend at 40 ºC is much less severe than the distress previously seen with the 30% ATJ/F-24 blend with 24-ppm CI/LI after 1000-hours at 77°C fuel inlet temperature.

The governor thrust washer conditions before and after 1000-hours are seen in Figure 80 and Figure 81. The polishing wear seen on the thrust washer in Figure 81 appears less severe than typical for a 1000-hour operation with a nominal lubricity fuel. Polishing and light fretting seen on the advance piston suggests the fuel pressure fluctuations in the fuel injection pump housing advance section. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The light wear on these components is normal considering the 1000-hour duration of testing. The wear on the thrust washer and the

advance piston wear likely did not affect the governor cut-off operation. The metering valve wear could have contributed to the compromised governor operation.

Figure 82 through Figure 87 illustrate the level of wear seen in the transfer pump section of fuel injection pump SN:17200858. Figure 82 shows the surface condition of the transfer pump liner prior to testing and Figure 83 shows the surface with 85% circumferential scoring after 1000-hours of operation on the ATJ/F-24 fuel with 24-ppm CI/LI. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure 84 through Figure 87. The edge wear shown in Figure 84 and Figure 85 corresponds to the surface on the transfer pump blades that contact the transfer pump liner and are typical for 1000-hours operation with a marginal to low lubricity fuel. Pump SN:17200858 had a broken blade spring that could have affected transfer pump component wear. The side polishing shown in Figure 86 and Figure 87 is light and reflects wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components of pump SN:17200858 are less severe than the elevated temperature 30% ATJ/F-24 test. The transfer pump component conditions suggest the test fuel has moderate fuel lubricity, also evidenced by the variation of transfer pump pressures noted during testing.

Figure 88 and Figure 89 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 89 reveals a wear scar that indicates backlash may have altered with the 30% ATJ/F-24 fuel with 24-pm CI/LI after 1000-hours. For both pumps operated at 40 ºC fuel temperature and utilized the ATJ/F-24 with 24-ppm CI/LI fuel, there were not any significantly worn components. The impacted injection pump performance was likely due to the accumulation of mild wear in multiple sections of the pumps.

Table 20. Pump SN:17200858 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-6282	SN : 17200858
Test condition : 1000 hours @ FIT 40°C and 1700 RPM	TEST : AF9625-24-C3ATJ4-40-1000
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear from liner, rotor slots & broken blade spring.	2.5
BLADE SPRINGS	One spring broken	4
LINER	85% wear from blades	3
TRANSFER PUMP REGULATOR	Wear scar from rotor & blades	2.5
REGULATOR PISTON	Polishing wear	2
ROTOR	Heavy rotational scarring at inlet and distributor ports	4
ROTOR RETAINERS	Wear from rotor	2.5
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear	1.5
SHOES	Dimple from plungers. Light wear from leaf spring. Scratching from rollers.	2.5
ROLLERS	Lighr wear	1.5
LEAF SPRING	wear from shoes	2.5
CAM RING	Polishing wear	2
THRUST WASHER	Polishing wear on both sides from weights & sleeve	1.5
THRUST SLEEVE	Heavy wear from linkage fingers & weights	3
GOVERNOR WEIGHTS	Wear from thrust washer	1
LINK HOOK	Dimple from governor rod. Worn fingers & pivot. Dimple from governor spring	3.5
METERING VAVLE	Light polishing wear	1
DRIVE SHAFT TANG	Heavy wear from rotor slot	3.5
DRIVE SHAFT SEALS	Normal	1
CAM PIN	Normal	1
ADVANCE PISTON	Polishing & fretting wear. Brown deposits	2.5
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	2.24

Figure 72. Pump SN:17200858 Distributor Rotor before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 73. Pump SN:17200858 Distributor Rotor with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 74. Pump SN:17200858 Rollers and Shoe before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 75 Pump SN:17200858 Rollers and Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 76. Pump SN:17200858 Roller Shoe before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 77. Pump SN:17200858 Roller Shoe with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 78. Pump SN:17200858 Cam Ring before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 79. Pump SN:17200858 Cam Ring with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 80. Pump SN:17200858 Thrust Washer before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 81. Pump SN:17200858 Thrust Washer with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 82. Pump SN:17200858 Transfer Pump Liner before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 83. Pump SN:17200858 Transfer Pump Liner with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 84. Pump SN:17200858 Transfer Pump Blade Edges before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 85. Pump SN:17200858 Transfer Pump Blade Edges with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 86. Pump SN:17200858 Transfer Pump Blade Sides before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 87. Pump SN:17200858 Transfer Pump Blade Sides with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 88. Pump SN:17200858 Driveshaft Drive Tang before Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

Figure 89. Pump SN:17200858 Driveshaft Drive Tang with 1000-Hours Testing with 30/70 ATJ/F-24 with 24-ppm CI/LI Fuel at 40 ºC

6.0 DISCUSSION OF RESULTS

In a prior study [3] the effect of synthetic fuel on the durability of the Stanadyne arctic rotary fuel injection pump that contains hardened parts was examined. This fuel injection pump is found on the HMMWV. In conducting the pump stand test with neat synthetic fuel, it was found that the tests had to be stopped prematurely due to fuel injection performance issues that ultimately could affect the operation of an engine.

Comparison results from various synthetic fuel programs were reviewed [3,4]. The comparisons of synthetic fuels performance in rotary fuel injection pumps discussed, suggested that synthetic kerosene fuels, when utilized neat, resulted in premature component wear. On a positive note, reference 3 also performed tests with CI/LI additives in synthetic fuel that showed a substantial improvement of rotary fuel injection pump durability with additive treated synthetic fuel.

A study [5] was performed to determine the impacts of a QPL-25017 CI/LI additive on fuel injection pump durability with synthetic fuel. A CI/LI additive was used at the maximum permitted 24-ppm concentration in a synthetic fuel and in a 50/50-percent blend of synthetic/Jet-A fuel. In conducting the pump stand tests at 40 °C with the two fuels, it was found that both tests had completed 1000-hours of operation with minimal impact on the performance or durability of the diesel engine fuel injection systems that included the fuel injection pump and fuel injectors.

A recent study [6] was performed to determine the impact of minimal QPL-25017 CI/LI additive levels on fuel injection pump durability with a synthetic fuel. The minimal additive levels were determined by the additive concentration that resulted in an ASTM D 5001 BOCLE wear scar in the synthetic fuel of 0.75-mm (8.5-ppm CI/LI additive) and 0.83-mm (2.75-ppm CI/LI additive). Both additive concentrations evaluated were below the QPL-25017 minimum effective concentration for the CI/LI additive used. Both additive levels evaluated were considered inadequate for rotary fuel injection pump protection.

A US ARMY study looked at CI/LI additive concentrations in synthetic and petroleum aviation kerosene fuels at elevated temperatures [7]. The results concluded that the maximum allowable level of CI/LI was required to maintain fuel injection pump durability at elevated temperature. One

QPL-25017 CI/LI product appeared to result in improved component conditions over the other products evaluated. The study looked at only the addition of CI/LI in Jet-A or SPK fuel, and did not look at the other MIL-DTL-83133H additives that make JP-8.

A previous study evaluated the effectiveness of CI/LI concentrations on 25%/75% ATJ/JP-8 fuel blends in rotary fuel injection pumps at elevated temperature [2]. The 25% ATJ/JP-8 blend had an ASTM D5001 lubricity of 0.563-mm wear scar when treated with 9-ppm of the CI/LI additive DCI-4A. The ASTM D6079 wear scar diameter result for the same blend was 670-µm. The ATJ/JP-8 blend when treated with 24-ppm of the CI/LI additive DCI-4A, had an ASTM D5001 lubricity of 0.504-mm wear scar. The ASTM D6079 wear scar diameter result for the same blend was 729-µm.

The testing with the 25/75 ATJ/JP-8 fuel with 9-ppm CI/LI, the minimum effective treat rate of the additive, indicated insufficient fuel lubricity for operation at 77 °C fuel inlet temperature. Relatively short time failures, severe component wear, and excessive drive shaft wear resulted in either a seizure or erratic pump performance [2].

Although the 25/75 ATJ/JP-8 fuel with 24-ppm CI/LI permitted completion of the 1000-hours at 77 ºC in the rotary diesel fuel injection pump test, one fuel injection pump's performance could not be measured due to erratic operation. One fuel injection pump would not allow idle operation if it was installed on an engine and the engine would be low on power. Component inspections suggest the transfer pump and drive tang wear was excessive and the cam ring and roller interface wear was high for both pumps [2].

For the 77 ºC test in this study the 30% ATJ/F-24 blend had an ASTM D5001 lubricity of 0.540-mm wear scar when treated with 24-ppm of the CI/LI additive DCI-4A. The ASTM D6079 wear scar diameter result for the same blend was 723-µm. For this study's 40 ºC test the 30% ATJ/F-24 blend when treated with 24-ppm of the CI/LI additive DCI-4A, had an ASTM D5001 lubricity of 0.555-mm wear scar. The ASTM D6079 wear scar diameter result for the same blend was 718-µm.

The current testing with the 30/70 ATJ/F-24 fuel with 24-ppm CI/LI, the maximum effective treat rate of the additive, indicated marginally sufficient fuel lubricity for operation at 77 °C fuel inlet temperature. The 30/70 ATJ/JP-8 fuel with 24-ppm CI/LI permitted completion of the 1000-hours in the rotary diesel fuel injection pump test, one fuel injection pump's performance would result in a fast idle and increased peak torque, but with adequate power and effective governor operation. The other fuel injection pump would allow adequate idle operation, torque, and power but would exhibit compromised governor operation. Component inspections suggest the transfer pump and drive tang wear was moderate and the cam ring and roller interface wear was also moderate for both pumps that operated at 77 °C. Fifteen of the fuel injectors passed all post-test inspection, one injector passed all inspections except the spray pattern quality.

The testing with the 30/70 ATJ/F-24 fuel with 24-ppm CI/LI, indicated marginal to adequate fuel lubricity for operation at 40 °C fuel inlet temperature. Although the 25/75 ATJ/JP-8 fuel with 24-ppm CI/LI permitted completion of the 1000-hours in the rotary diesel fuel injection pump test, one fuel injection pump's performance would result in increased peak torque, with adequate power, but compromised governor operation. The other fuel injection pump would not allow idle operation if it was installed on an engine, exhibit slower run-up from cranking, and have compromised governor operation. The engine would exhibit adequate power and torque. Component inspections suggest the transfer pump and drive tang wear was moderate and the cam ring and roller interface wear was moderate for both pumps. An unusual occurrence for the 40 °C testing was the five fuel injectors that did not meet the 1500-psig minimum Nozzle Opening Pressure, and subsequent tip leakage criteria, at conclusion of testing.

Observed in previous work [2,4,5,7], the maximum effective concentration of CI/LI additive is suggested for synthetic fuel blends in order to offer adequate rotary diesel fuel injection pump wear protection. At elevated temperature even the maximum treatment levels appeared inadequate for a 25% ATJ/JP-8 blend [2]. However with the 30%/70% ATJ/F-24 blend the 24-ppm CI/LI additive appeared to be more effective in protecting the fuel injection pump components at elevated temperature, suggesting the 5% additional ATJ offered some improvement. The rotary fuel injection pumps respond to more viscous fuels, and ATJ tends to be slightly more viscous than the F-24.

In this test sequence the 40 ºC and 77 ºC fuel inlet temperature pump performance and wear results were quite similar. Fuel delivery histories for three of the four pumps exhibited an unusual characteristic where the delivery decayed, then suddenly recovered, to be followed by slow decay till test termination. Coincidentally the three pumps that displayed the sudden delivery surge, were the same three pumps that exhibited the compromised governor operation at the conclusion of testing.

7.0 CONCLUSIONS

The following conclusions can be made from the cumulative knowledge of utilizing JP-8, F-24, synthetic aviation kerosene fuel blends, and 30/70 ATJ/F-24 in diesel rotary fuel injection pumps at various fuel inlet temperatures:

- For elevated fuel inlet temperature operation, even with petroleum F-24/JP-8 at 77 °C, the maximum effective CI/LI concentration is required to provide adequate wear protection.
- For elevated fuel inlet temperature operation, with synthetic fuel blends at 77 °C, the minimum effective CI/LI concentration is inadequate.
- A 30/70 blend of ATJ/F-24 with 24-ppm CI/LI operated at 77 °C fuel inlet temperature will allow 1000-hours of rotary pump operation. The observed performance degradation of the fuel injection pumps at 1000-hours could impact engine idle speed and/or governor operation. The component inspections suggested moderate wear.
- A 30/70 blend of ATJ/F-24 with 24-ppm CI/LI operated at 40 °C fuel inlet temperature will allow 1000-hours of rotary pump operation. However the performance degradation of the fuel injection pumps at 1000-hours could impact engine operation, and component inspections suggested moderate wear.
- The additional 5% ATJ in the test blend may have improved injection pump wear resistance due to a slight viscosity improvement.

8.0 RECOMMENDATIONS

The technical feasibility of using ATJ/F-24 fuel at 40 ºC and 77 ºC fuel inlet temperatures in rotary fuel injection equipment when blended with a CI/LI additive has been investigated:

- At the minimum effective concentration of a QPL-25017 CI/LI additive, ATJ/F-24 blends should NOT be utilized in regions where rotary fuel injection pump equipped engines are exposed to elevated fuel inlet temperatures.
- It is recommended that blends of ATJ/F-24 fuels include the addition of the maximum effective concentration of CI/LI for use in diesel rotary fuel injection equipment at nominal ambient temperatures.
- Based on the initial limited set of test results, at elevated fuel inlet temperatures, even the use of maximum concentration CI/LI in a 25% ATJ/F-24 fuel blend appears to result in accelerated wear in fuel-lubricated rotary fuel injection pumps.
- From the current limited set of test results, at various fuel inlet temperatures, the use of maximum concentration CI/LI in a 30% ATJ/F-24 fuel blend appears to retard the accelerated wear observed in prior fuel-lubricated rotary fuel injection pump studies.
- ATJ fuel can be utilized at 30% when blended with F-24, provided the F-24 component has sufficient cetane number such that the resulting blend is 40 CN or greater.

9.0 REFERENCES

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